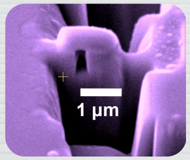
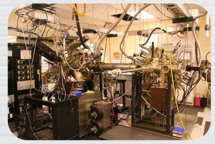
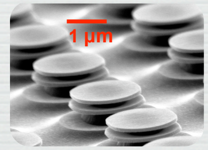
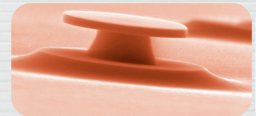




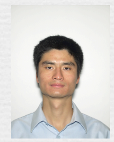
# Spintronics without Magnetism

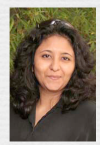
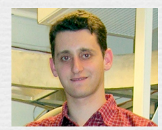
Nitin Samarth

# Outline

- "Spintronics": an overview
- Spintronics without magnetism: controlling spins in semiconductors via:
    - The spin-orbit interaction (spin Hall effect)
    - Circularly polarized photons (coherent spin dynamics)





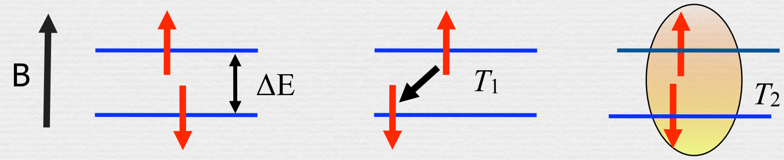




# Some reminders

Electron has spin = 1/2 with two possible projections along magnetic field B: "up" and "down"

$$\Delta E = g_e \frac{e\hbar}{2m_e} B = g_e \mu_B B$$

Free electron: $g = 2$
Solid state: $-0.4 < g < \sim 50$




Schrodinger (non-relativistic) equation: "spinless"
Dirac equation (relativistic): includes spin and yields coupling between spin and orbital motion of electrons

$$H_{\text{S-O}} = \lambda_0 \vec{\sigma} \bullet \left[ \vec{p} \times \vec{\nabla} V \right]$$

# So, what exactly is “spintronics”?

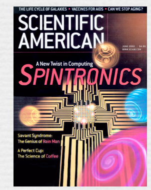
(a) An acronym for “spin-transport based electronics.”

(b) A misnomer for a commonly used technology.

(c) A potentially exciting path towards processing and storing classical and/or quantum information in solid state devices in the distant future.

(d) A convenient excuse for funding your favourite condensed matter physics project.

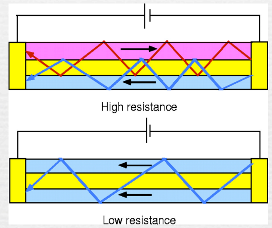
(e) All of the above.

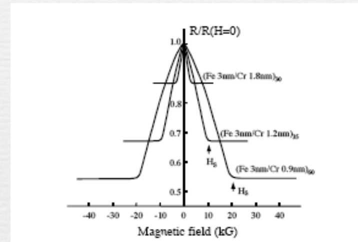


# "Spintronics"

- "**Spin-tr**ansport based electr**onics**": originally coined for **ferromagnetic metal** sensors that read magnetically stored information.
  - Giant magnetoresistance (GMR): spin-dependent scattering; used in magnetic read head sensors -- 2007 Nobel prize in Physics for Fert and Grunberg

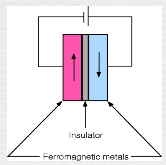

340 MB microdrive (IBM ca. 1999)

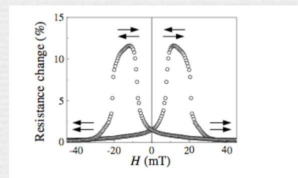



Baibich et al, PRL (1998)

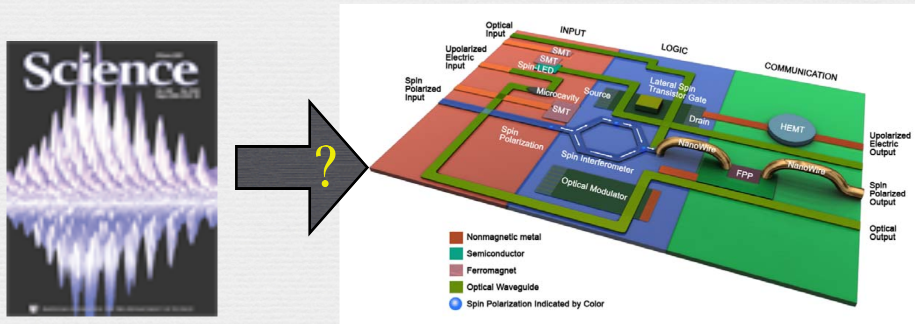
  - Tunnel magnetoresistance: read heads, magnetic random access memory




# Semiconductor Spintronics

- **Fundamental objectives:** controlling spins (band electrons, magnetic ions & nuclei) in semiconductors.
- **Challenge and opportunity:** how to transition from fundamental exploration of spin control in semiconductors towards a technology?

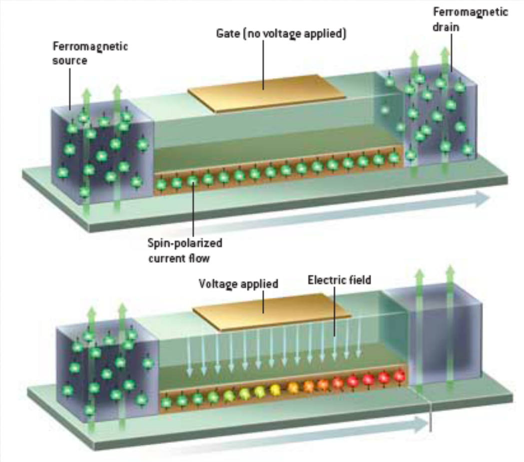



(Gupta, Knobel, Samarth, Awschalom, 2001)

# Semiconductor Spintronic Device - I

$$H_{\text{Rashba}} = \alpha\left[\vec{\sigma} \times \vec{k}\right] \cdot \hat{z}$$

- The “spinFET”: inject a spin polarized current from a ferromagnetic source into the channel of a semiconductor field effect transistor.
- Apply an electric field via the gate -- S-O coupling makes this act like a magnetic field, causing spin precession.
- Use a ferromagnetic drain to act as a spin detector.
- Question: is this faster or more efficient that current (or even projected) CMOS technology??

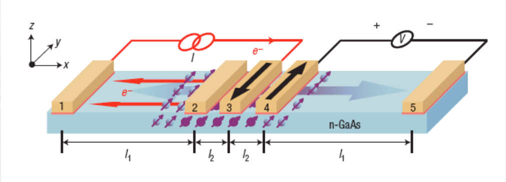



“Electronic analog of the electro-optic modulator,” Datta & Das: APL **56**, 665 (1990)

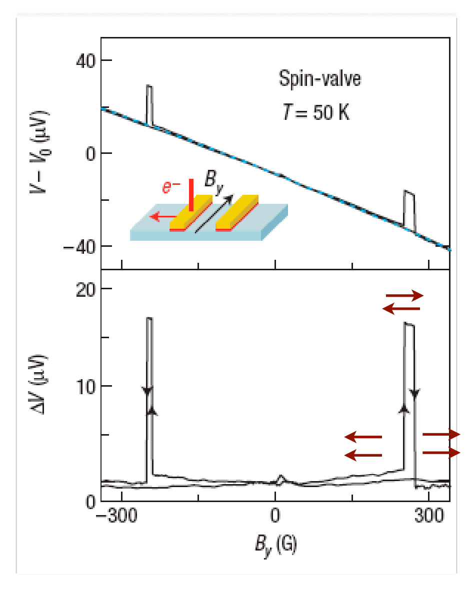
# Progress towards spin FETs

Electrical spin injection from FM metals into semiconductors & spin detection now demonstrated -- Crowell (Minnesota), Jonker (NRL)

Lou *et al*. PRL (2006); Nature Physics (2007).

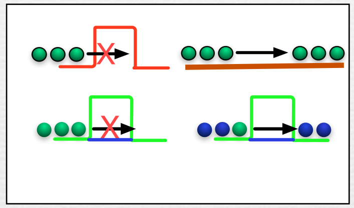


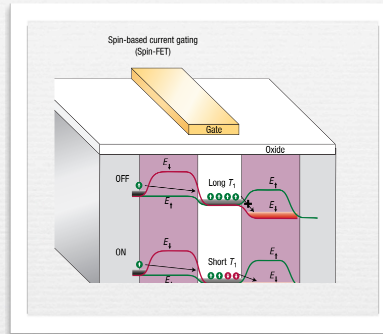

Still no demonstration of the complete spinFET device



# Semiconductor Spintronic Devices -- II

Does the performance of spin-based semiconductor devices potentially warrant the effort?






APPLIED PHYSICS LETTERS **88**, 162503 (2006)

## Performance of a spin-based insulated gate field effect transistor


Kimberley C. Hall
*Department of Physics, Dalhousie University, Halifax B3H 3J5, Canada*

Michael E. Flatté[a)]
*Optical Science and Technology Center and Department of Physics and Astronomy, University of Iowa, Iowa City, Iowa 52242*


(Received 29 January 2006; accepted 28 February 2006; published online 18 April 2006)

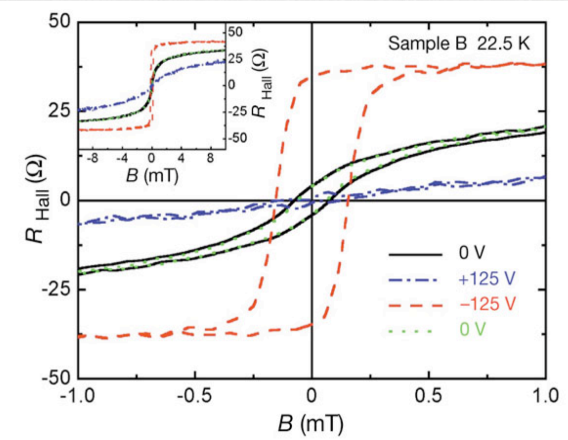
Fundamental physical properties limiting the performance of spin field effect transistors are compared to those of ordinary (charge-based) field effect transistors. Instead of raising and lowering a barrier to current flow these spin transistors use static spin-selective barriers and gate control of spin relaxation. The different origins of transistor action lead to distinct size dependences of the power dissipation in these transistors and permit sufficiently small spin-based transistors to surpass the performance of charge-based transistors at room temperature or above. This includes lower threshold voltages, smaller gate capacitances, reduced gate switching energies, and smaller source-drain leakage currents. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2192152]

# Spintronics with Magnetic Semiconductors

★ Combining magnetism with semiconductors may allow devices with new functionality: **electrical control of exchange interactions**.

★ Electrical control of steady state ferromagnetism demonstrated by Ohno.

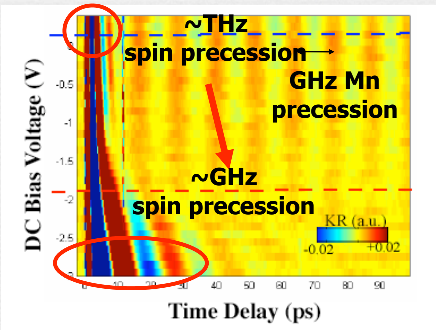
★ Can we demonstrate electrically control of spin *dynamics* in magnetic semiconductors?

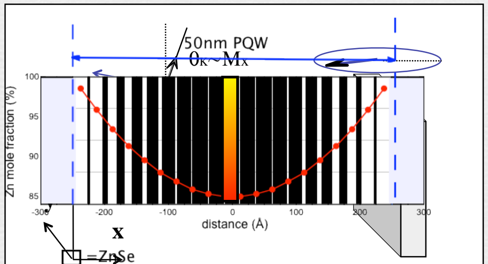



Ohno *et al.*, Nature (2000)

# Gating of spin dynamics in quantum wells

- Magnetic ions in II-VI semiconductor: *sp-d* exchange coupling results in highly enhanced Zeeman splitting and large spin polarization of Fermi sea [review: Furdyna, JAP R29 (1988)]
- Design "parabolic magnetic quantum wells" -- magnetic ions in center of parabolic potential
- Electric field varies exchange overlap, pump-probe Kerr effect measures time dependent spin dynamics



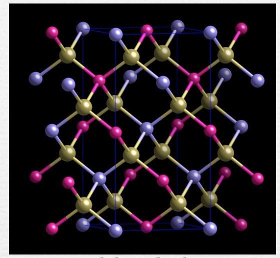




Crooker et al. PRL 77, 2814 (1996)

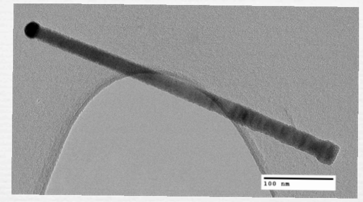
Myers et al., PRB **72**, 041302(2005)

# Materials for Semiconductor Spintronics

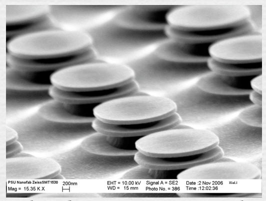
Do not need "exotic" materials! Conventional semiconductors suffice. Additional refinements (e.g. magnetic dopants, lithography)) also now standard.



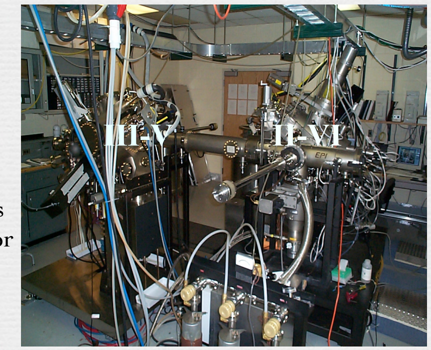
Zinc-blende lattice

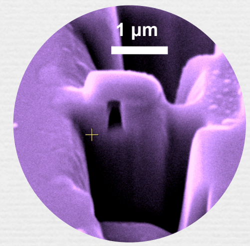



(Zn,Mn)Se Nanowire



Hybrid GaMnAs/GaAlAs ferromagnet/semiconductor microdisk lasers




(Ga,Mn)As-based Submicron Magnetic Tunnel Junction

# Outline

- "Spintronics": an overview
- Spintronics without magnetism:
  - Spin-orbit interaction (spin Hall effect)
  - Circularly polarized photons (coherent spin dynamics)

# Spin-orbit Coupling & Scattering

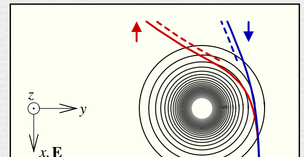
*The Scattering of Fast Electrons by Atomic Nuclei.*

By N. F. Mott, B.A., St. John's College, Cambridge.

(Communicated by N. Bohr, For. Mem. R.S.—Received April 25, 1929.)

*Section* 1.—The hypothesis that the electron has a magnetic moment was, as is well known, first introduced to account for the duplexity phenomena of atomic spectra. More recently, however, Dirac has succeeded in accounting for these same phenomena by the introduction of a modified wave equation, which conforms both to the principle of relativity and to the general transformation theory. Formally, at least, on the new theory also, the electron has a magnetic moment of $\epsilon h/mc$, but when the electron is in an atom we cannot observe this magnetic moment directly; we can only observe the moment of the whole atom, or, of course, the splitting of the spectral lines, which we may say is "caused" by this moment. The question arises, has the *free* electron "really" got a magnetic moment, a magnetic moment that we can by any conceivable experiment observe? The question is not so simple as it might seem, because a magnetic moment $\epsilon h/mc$ can never be observed directly, *e.g.*, with a magnetometer; there is always an uncertainty in the external electromagnetic field, due to the uncertainty in the position and

(nobelprize.org)



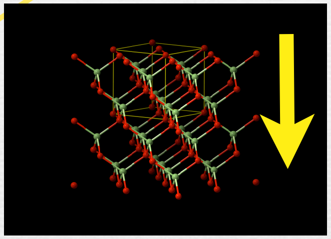

Engel *et al*, PRL (2005)

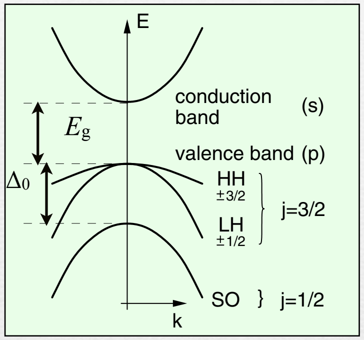
# Spin-Orbit Coupling in Semiconductors

Nonrelativistic approximation to Dirac equation in vacuum yields:

$$H_{SO} = -\frac{\hbar^2}{4m_0^{\ 2}c^2}\vec{\sigma}\bullet\left(\vec{p}\times\nabla V\right)$$

3.7 x $10^{-8}$ nm$^2$



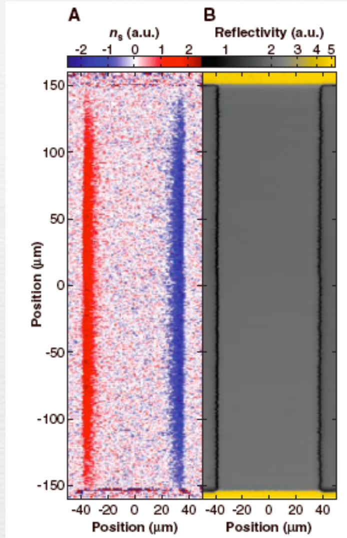



| Semiconductor | λ (nm$^2$) |
|---|---|
| InAs | 1.17 |
| GaAs | 0.052 |
| ZnSe | 0.011 |

$$H_{\text{S-O}} = \lambda\vec{\sigma}\bullet\left[\vec{k}\times\vec{\nabla}V\right]$$

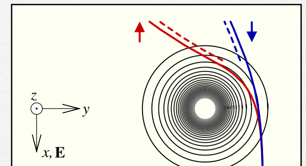
$$\lambda = \frac{P^2}{3}\left[\frac{1}{E_g^{\ 2}} - \frac{1}{\left(E_g+\Delta_0\right)^2}\right]$$

# The Spin Hall Effect




Spin Hall effect in n-doped GaAs
Kato *et al*, Science **306**, 1920 (2004)

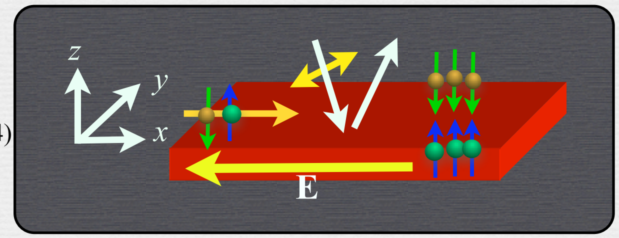
$$H_{\text{Rashba}} = \lambda \vec{\sigma} \bullet \left( \vec{k} \times \nabla V \right)$$



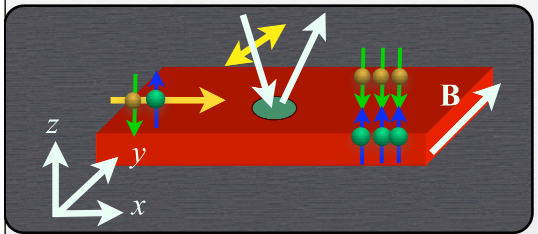

Engel *et al*, PRL (2005)

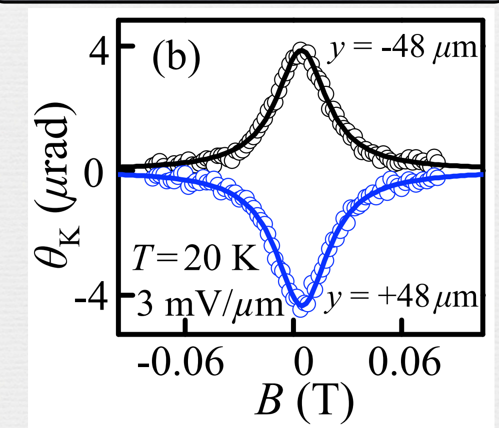
An “ordinary” current flowing in an “ordinary” n-doped semiconductor leads to spin accumulation a sample boundaries:

- (Extrinsic) Spin Hall effect
- Predicted by Dyakonov & Perel, Phys. Lett. A **13**, *467* (1971),
- Observed in n-GaAs and n-InGaAs at low temperatures by Kato *et al*, Science (2004))



# Local Hanle Effect

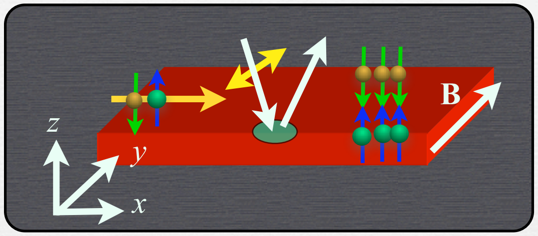


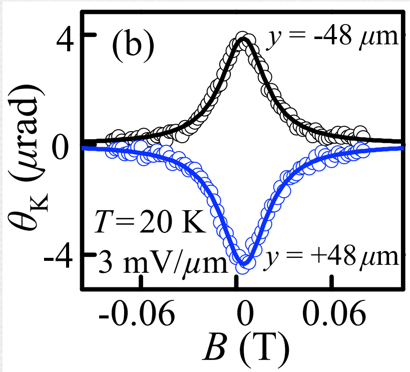

- Apply a magnetic field along $y$ (normal to current density)
- Measure spatially-resolved Kerr effect as a function of $B$
- Magnetic field leads to precessional depolarization of spin Hall signal (Hanle effect)
- Lorentzian fit yields spin decoherence time τ .
- In conjunction with a drift-diffusion analysis of spatial profile of spin Hall effect, this allows us to extract a "spin Hall conductivity".

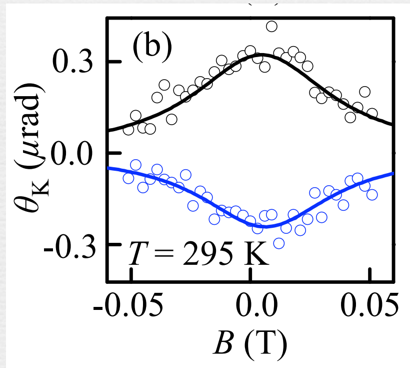
$$\frac{\theta_{peak}}{(\omega_L \tau)^2 + 1}$$

# The Spin Hall Effect at Room Temperature




- **ZnSe**: semiconductor with spin-orbit coupling constant ~5 times weaker than in GaAs.
- Magnitude of SHE (spin Hall conductivity) comparable to GaAs.
- Spin Hall effect in ZnSe observable at ~300 K.



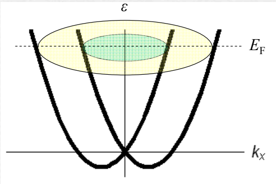

Stern *et al*, Phys. Rev. Lett. (2006)

# Understanding the Spin Hall Effect

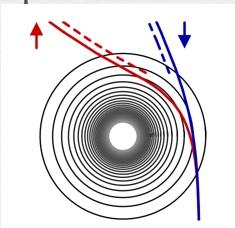
Non-interacting electrons (effective mass approximation, near k = 0)

$$H = k^2/2m^* - \tfrac{1}{2}\,\mathbf{b}(\mathbf{k})\cdot\boldsymbol{\sigma} + V(\mathbf{r}) + \lambda\,\boldsymbol{\sigma}\cdot(\mathbf{k}\times\nabla V)$$

"intrinsic" spin Hall effect




"extrinsic" spin Hall effect



Engel, Halperin, Rashba (PRL 2005): spin Hall conductivity calculated to lowest order in SO interaction and $(k_F l_e)^{-1}$;
Small parameter controlling polarization of scattered carriers ~ $\lambda/(a_B)^2$, where $a_B$ is the Bohr radius for conduction band electrons.

# Outline

- "Spintronics": an overview
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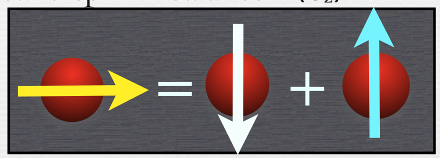
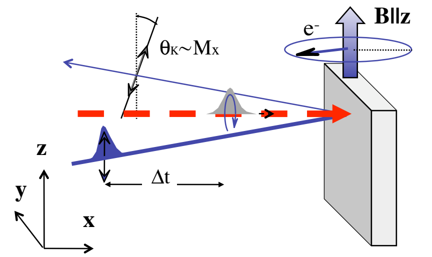
# Probing Spin Dynamics in Semiconductors

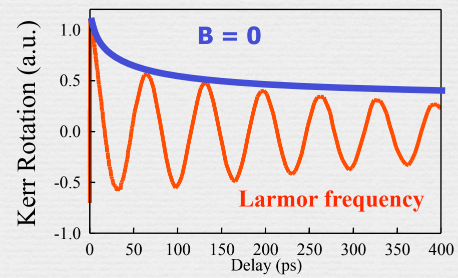
★ Circularly polarized pump resonant with band gap creates conduction band spin imbalance $\langle S_z \rangle$






Crooker et al, PRL **77**, 2814 (1996)

★ Time-delayed linear polarized probe measures time evolution of $\langle S_z \rangle$




★ Larmor precession in transverse magnetic field: oscillating signal

★ Decay of spin polarization measures inhomogeneous spin lifetime $T_2^*$

★ Relevant relaxation times:
- Hole spins < 10 ps
- e-h recombination ~ 100 ps
- Electron spins > 100 ps

# Spin Coherence in Semiconductors

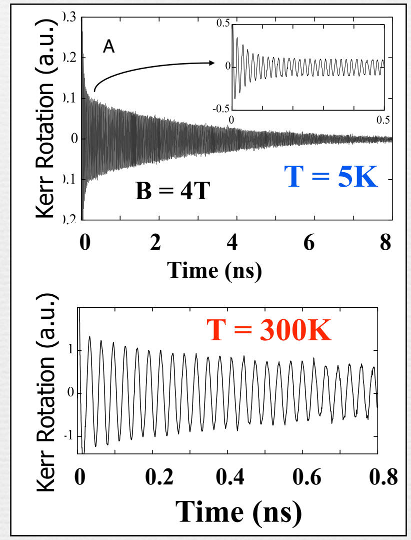
**Spin relaxation mechanisms:**

★ Impurity scattering (Eliot-Yafet):
$T_2^* \neq \tau_{elastic}$

★ Precessional dephasing by k-dependent "magnetic field" (Dyakonov-Perel)
$T_2^* \neq (\tau_{elastic})^{-1}$

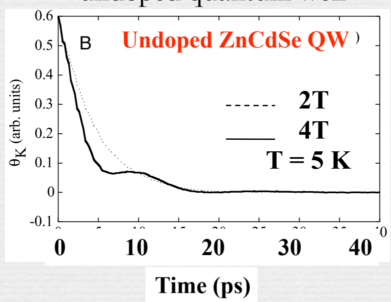
★ Electron-hole exchange (Bir-Aronov-Pikus)

Slow spin relaxation in n-doped QWs (ZnCdSe 2DEGs)



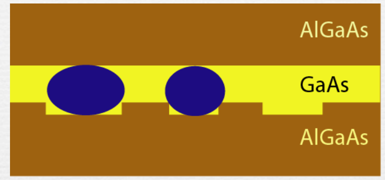

Kikkawa, Smorchokova, Samarth, Awschalom, Science (1997)

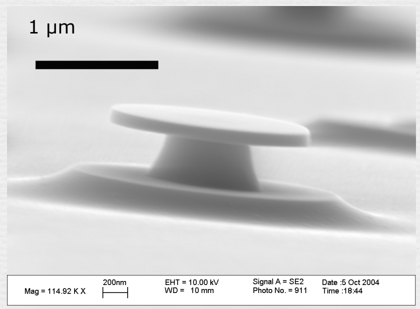
Rapid spin relaxation in undoped quantum well

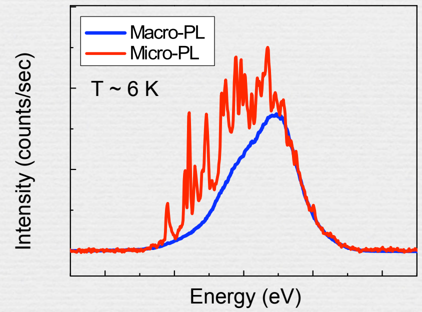


# Photonic Control of Spin Dynamics

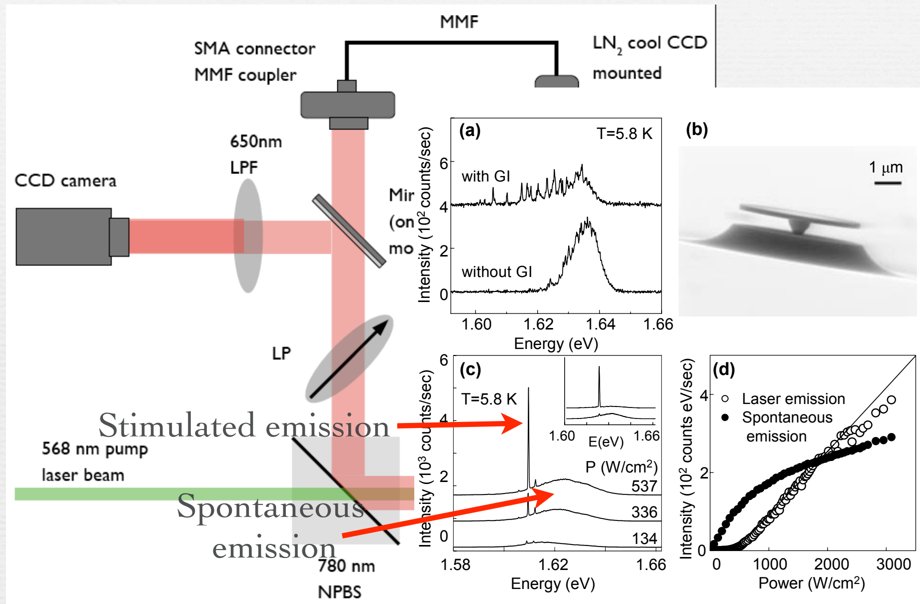
- ★ Interface fluctuations in quantum wells known to create quantum dot states -- evidenced by sharp lines in spatially limited emission ("micro-photoluminescence")
- ★ Microdisk lasers fabricated using lithography + selective etching.
- ★ Pump-probe spectroscopy used to study electron spin dynamics.



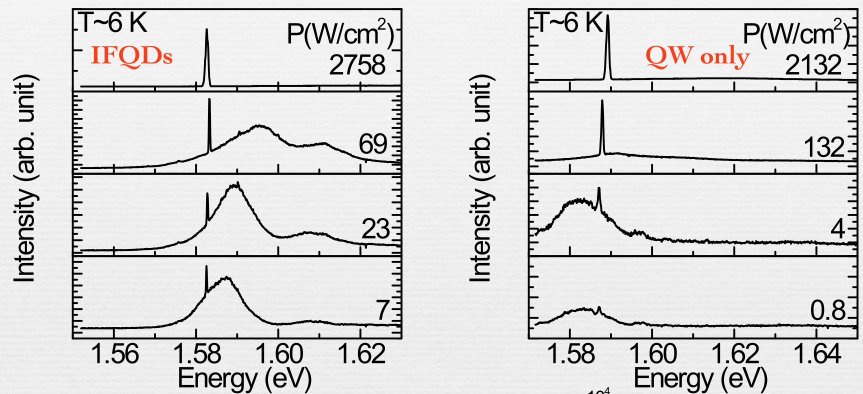



# CW Spectroscopy of Microdisks



# Effect of Quantum Dots on Lasing

Small cavities (~ 2 μm diam.)

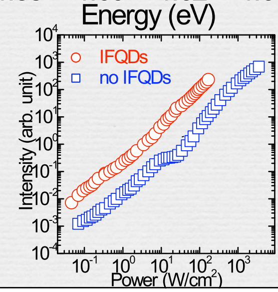



★ In microdisks with IFQDs (D~2.2 μm)

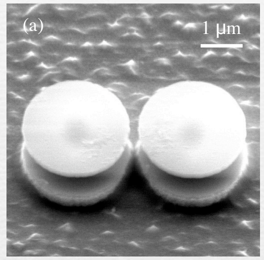
- $\beta$ ~ 0.15; $P_{\text{thresh}}$ ~ 25 W/cm² (152 nW).

★ In microdisk without IFQD

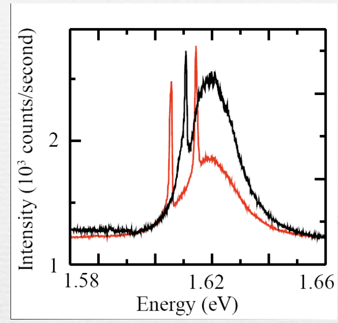
- $\beta$ ~ 0.35; $P_{\text{thresh}}$ ~ 4 W/cm² (3.14 μW).
- Large oscillator strength in IFQDs

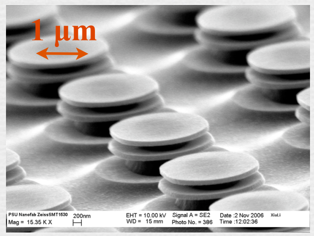


# The Microdisk Factory

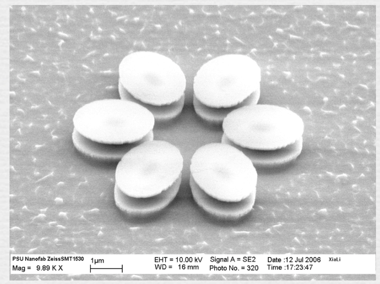



Photonic molecules



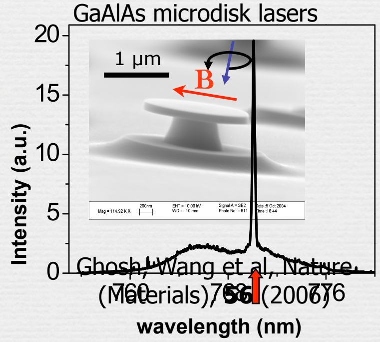

Hybrid ferromagnet/
semiconductor microdisks



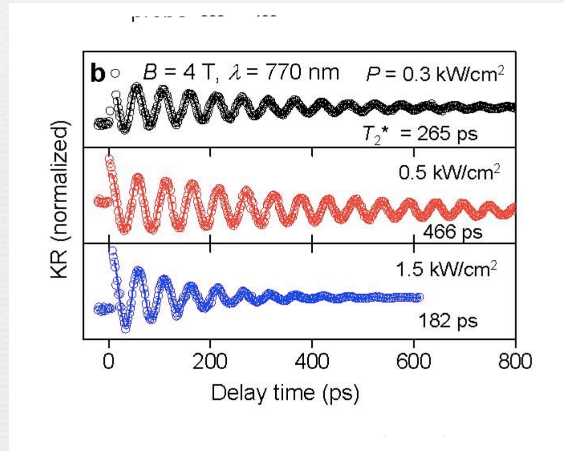
# Spin Dynamics in Microcavity Lasers

Pump-probe Kerr spectroscopy of GaAs microdisk lasers reveals surprising correlation between spin coherence time & laser characteristics (resonant modes, Q factor, threshold...)

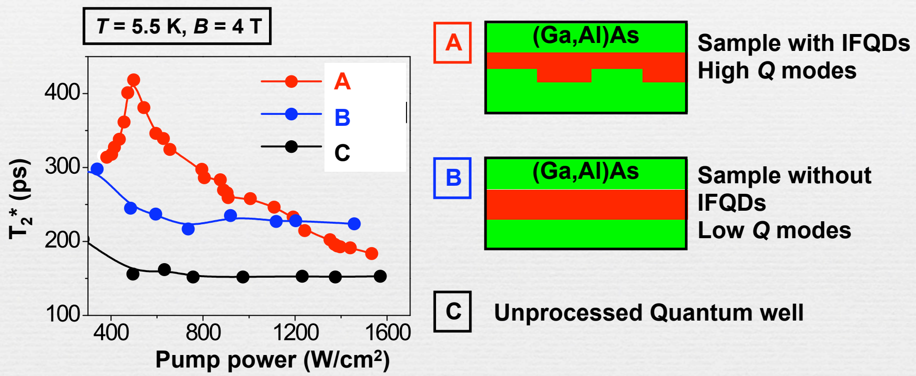
Q-factor engineering of electron spin coherence in GaAs/GaAlAs microdisk lasers




Ghosh, Wang et al, Nature (Materials) **5** (2006)



# Comparison with control samples




- Enhancement not observed in bare (unprocessed) quantum well
- Also not seen in control cavities with low Q resonant modes

# Summary

- Introduction to “spintronics” with semiconductors
- Spin control in “magnetic semiconductors”: exchange interaction between band states and local moments creates spin polarization; devices allow tuning of exchange overlap.
- Spin control “without magnetism”: spin-orbit coupling enables all-electrical spin polarization in semiconductors; photon confinement enhances spin coherence time in microcavities.
- Next steps: how to make these phenomena “large” enough to serve as basis for new technology?