# Narrow-Gap Semiconductors, Spin Splitting With no Magnetic Field and more…..

**Giti Khodaparast**
**Department of Physics**
**Virginia Tech**

Supported by:
NFS-DMR-0507866
AFOSR Young Investigator Award

VirginiaTech
*Invent the Future*
*Department of Physics*

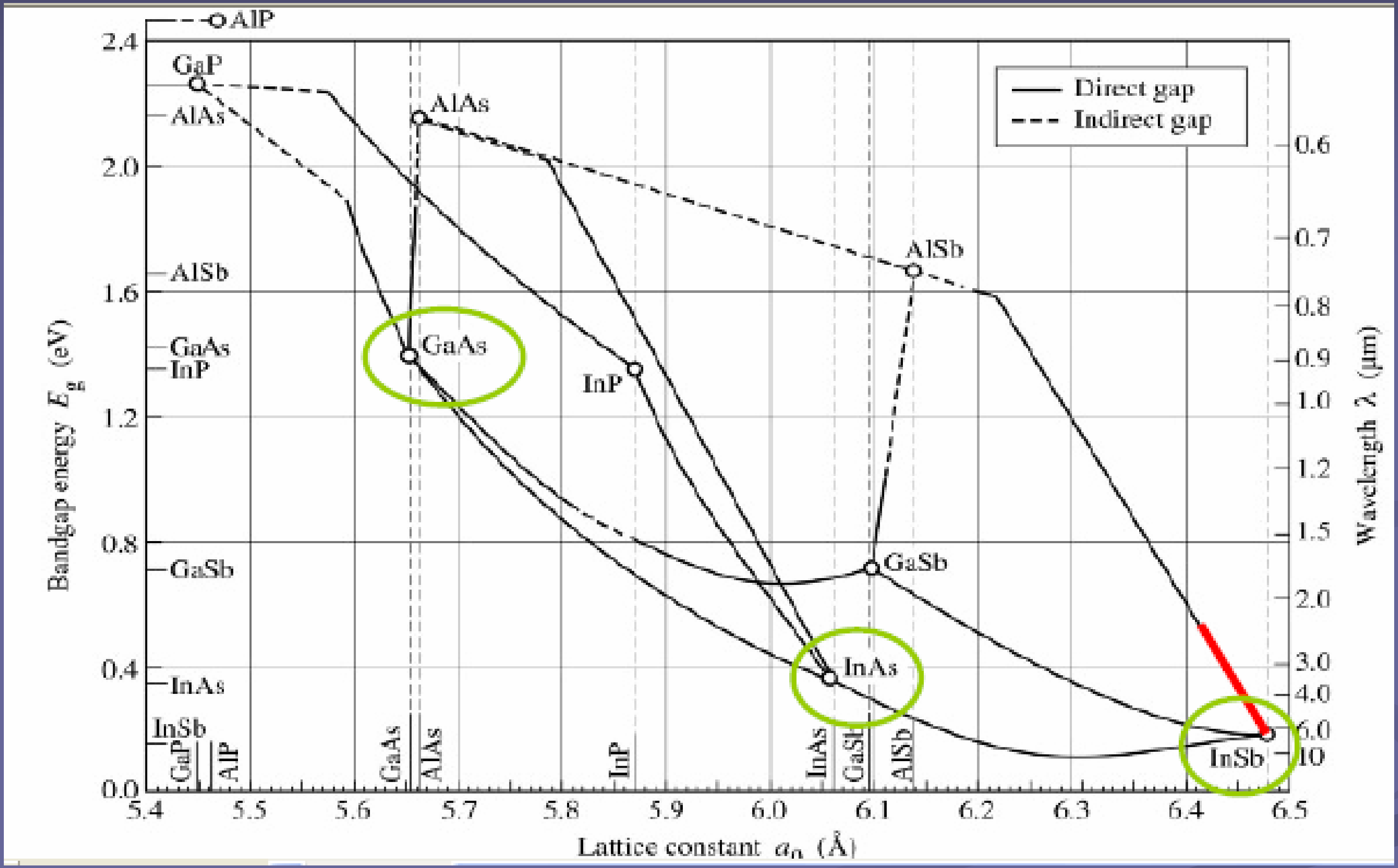
**University of Virginia , Oct 11th 2007**

# InSb Based Samples

J. K. Furdyna, InMnSb
Department of Physics, University of Notre Dame,

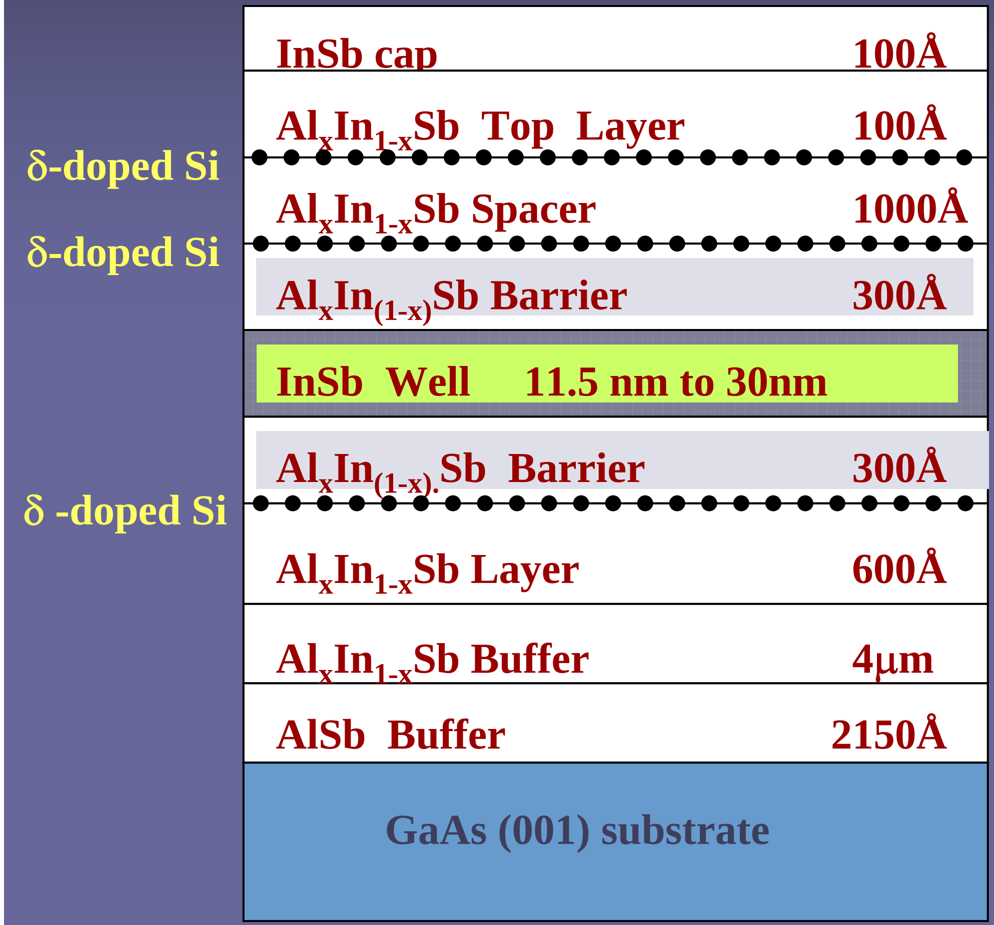
M. B. Santos , InSb QWs
Department of Physics & Astronomy, University of Oklahoma

# III-V Semiconductors




VirginiaTech
Invent the Future
Department of Physics

# InSb Quantum Wells




Density: 1-4x$10^{11}$ $cm^{-2}$
Mobility: 100,000-200,000 $cm^2/Vs$
Alloy concentration: 9%, 15%

- ❑ Intel and Qinetiq researchers have recently demonstrated prototype InSb quantum well transistors.
- ❑ InSb QW has the lowest energy dissipation and gate delay which is an important metric for logic microprocessors.
- ❑Single electron charging effect in a surface-gated InSb/AlInSb has been reported.

Tim Ashley's group , New Journal of Physics, 9, (2007)


VirginiaTech Invent the Future
Department of Physics

S. J. Chung, N. Goel, M. B. Santos, University of Oklahoma

# Basic Characteristics

| | $m^*/m_o$ | g-factor | E(k) |
|---|---|---|---|
| **GaAs** | **0.067** | **-0.5** | **Least non-parabolic** |
| **InAs** | **0.023** | **-15** | **More non-parabolic** |
| **InSb** | **0.014** | **-51** | **Most non-parabolic** |

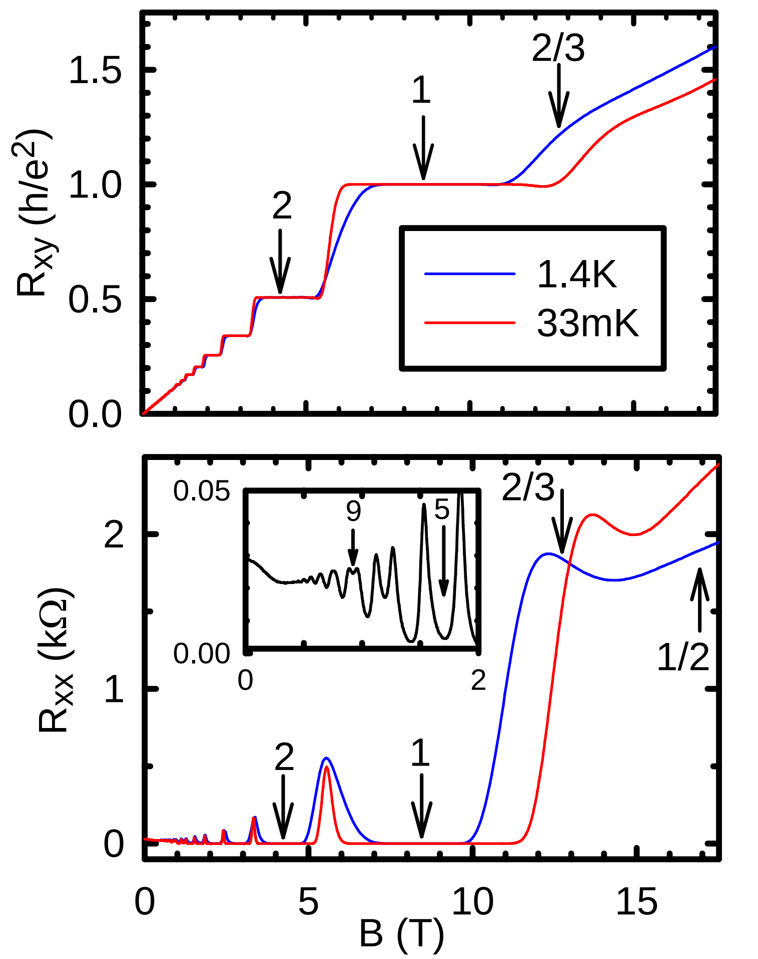
# InSb Based Heterostructures

**An ideal model of a narrow-gap semiconductor**

- Small effective mass, large g-factor
- Small e-e interaction
- Large spin-orbit coupling

VirginiaTech
Invent the Future
Department of Physics

# Quantum Hall Effect in InSb



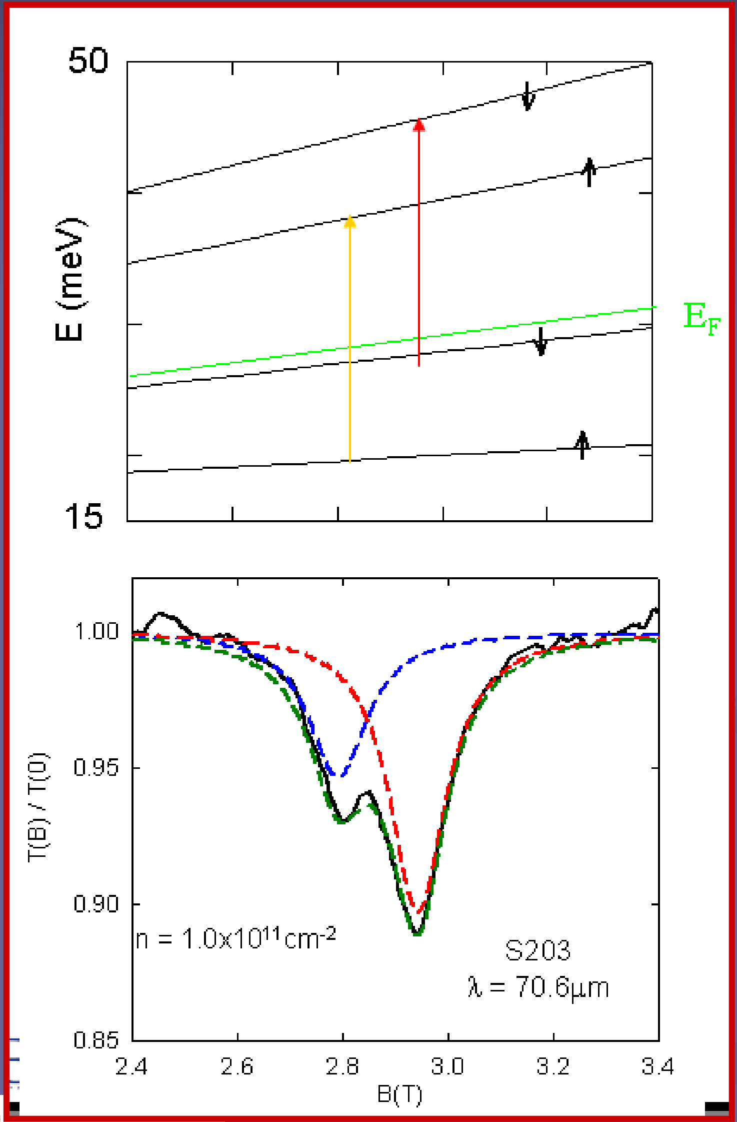

- Shubnikov de Haas oscillations down to low B (0.4T)
- Spin splitting resolved at starting at low B (>0.8T)
- Integer Quantum Hall Effect
- No evidence of Fractional Quantum Hall Effect, but <u>not</u> insulating at ν<1

S. J. Chung et al. Physica **E7**, 809 (2000)

**Ballistic transport in InSb mesoscopic structures**
Hong Chen, J.J. Heremans, J.A. Peters, N. Goel, S.J. Chung, and M.B. Santos, Applied Physics Letters **84**, 5380 (2004)

VirginiaTech
Invent the Future
Department of Physics

# Intensity Anomaly in Spin-Split CR, InSb/AlInSb QW



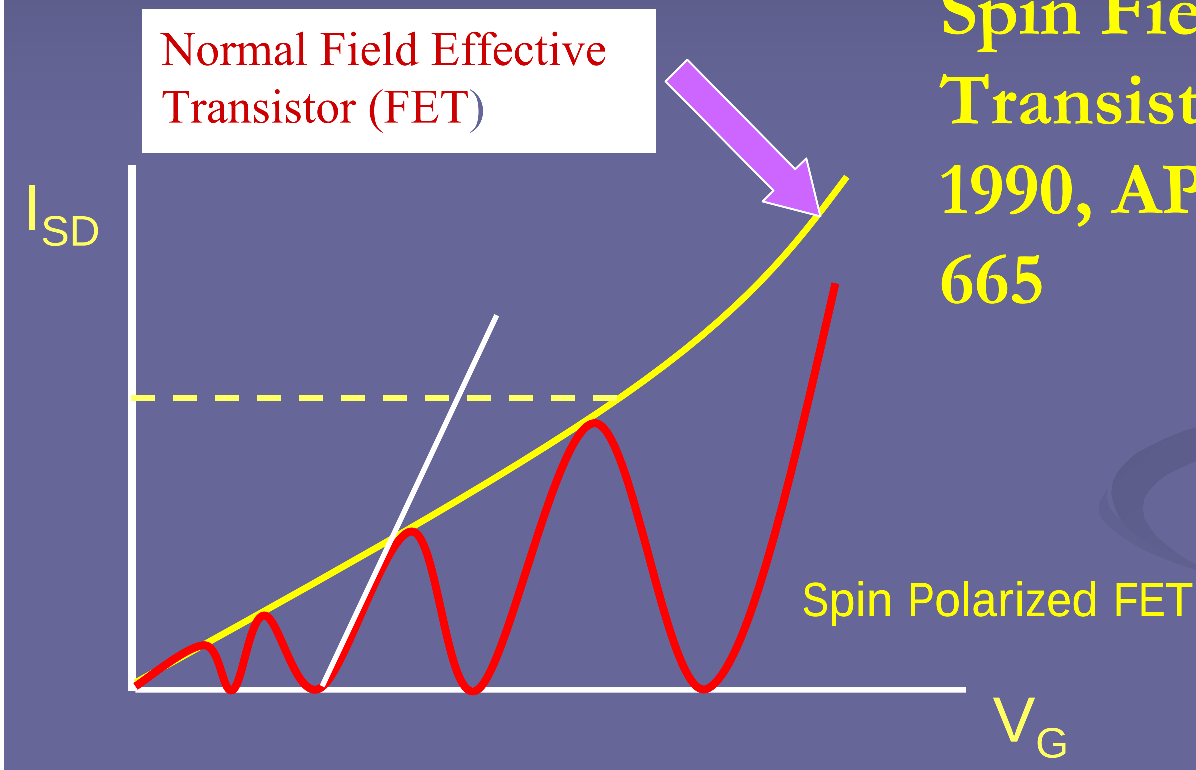

Landau level calculation predicts that blue transition is stronger…

… but experiment determines that red transition is stronger!

**Spin Effects in InSb Quantum Wells," G.A. Khodaparast, *et al., Physica* E20, 386 (2004).**

VirginiaTech
Invent the Future
Department of Physics

# Narrow Gap : Revisited

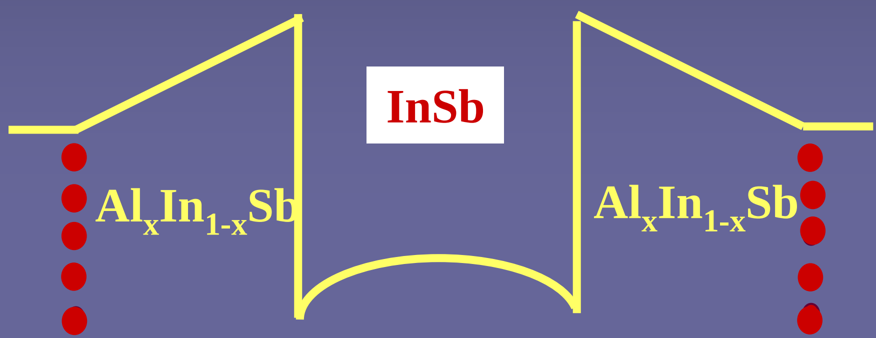



**Spin Field Effective Transistor: Datta and Das, 1990, APL. Phys. Lett., 56, 665**

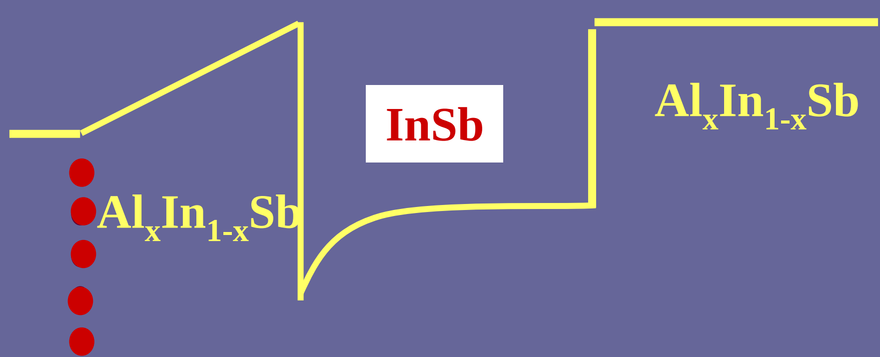
Virginia Tech
Invent the Future
Department of Physics

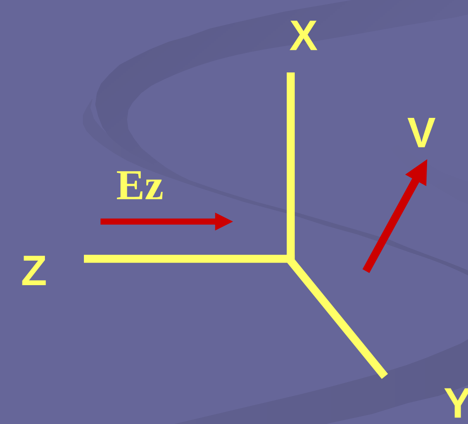
# InSb Quantum Well Structures

Symmetric quantum well




Asymmetric quantum well

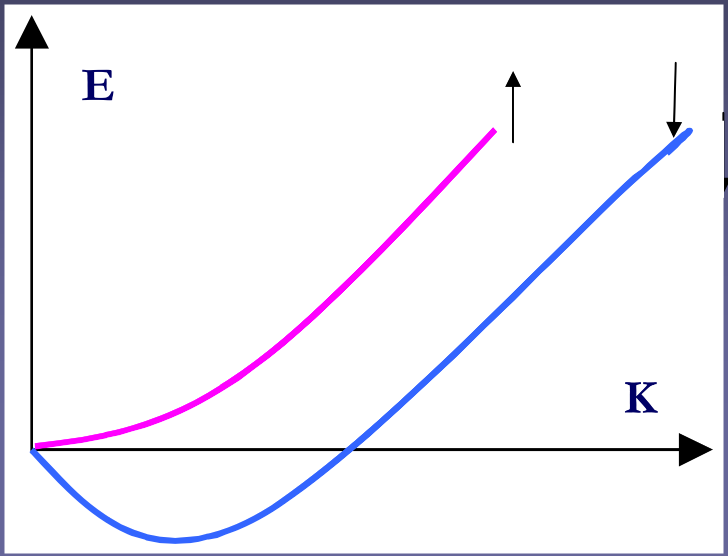



$B_{eff} = E \times V/c$

VirginiaTech
Invent the Future
Department of Physics

# Zero Field Spin Splitting




$$E = E_z^{sub} + \frac{\hbar^2 k_t^2}{2m^*} \pm \alpha |k_t|$$

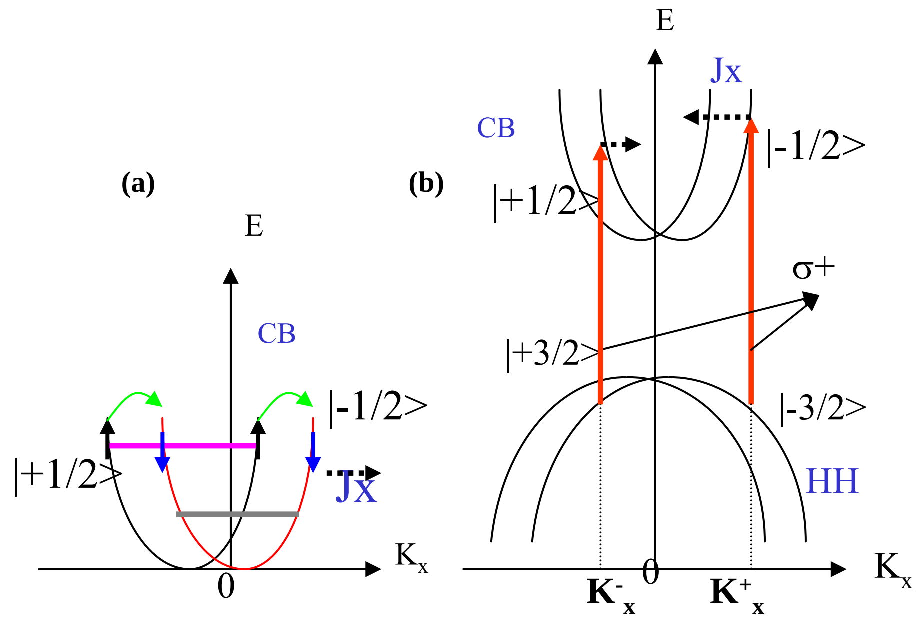
Asymmetry of the confining potential in a QW remove the degeneracy of band structure → **Rashba effect**

Bulk Inversion asymmetry is known as→ **Dresselhaus effect**

VirginiaTech
Invent the Future
Department of Physics

**Zero Field Spin Splitting, Rashba (J. Phys. C 17, 6039 1983) or Dresselhaus effects (Phys Rev 100, 580, 1995)**

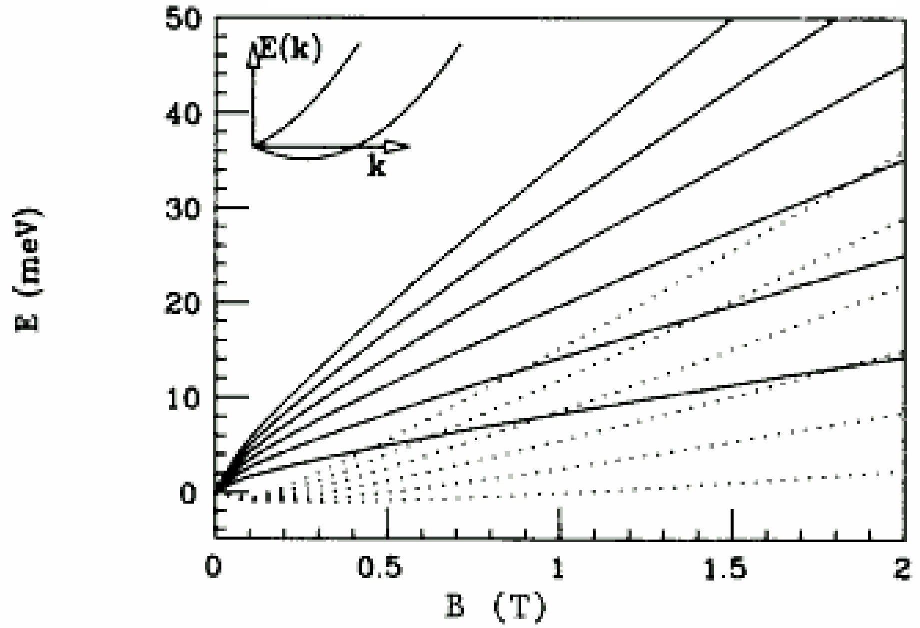
# Spin Polarized Current




VirginiaTech Invent the Future
Department of Physics

S. D. Ganichev and W. Prettl, J. Phys: Condens. Matter 15 (2003) R935-R983

# Rashba Splitting at B>0




In addition to:

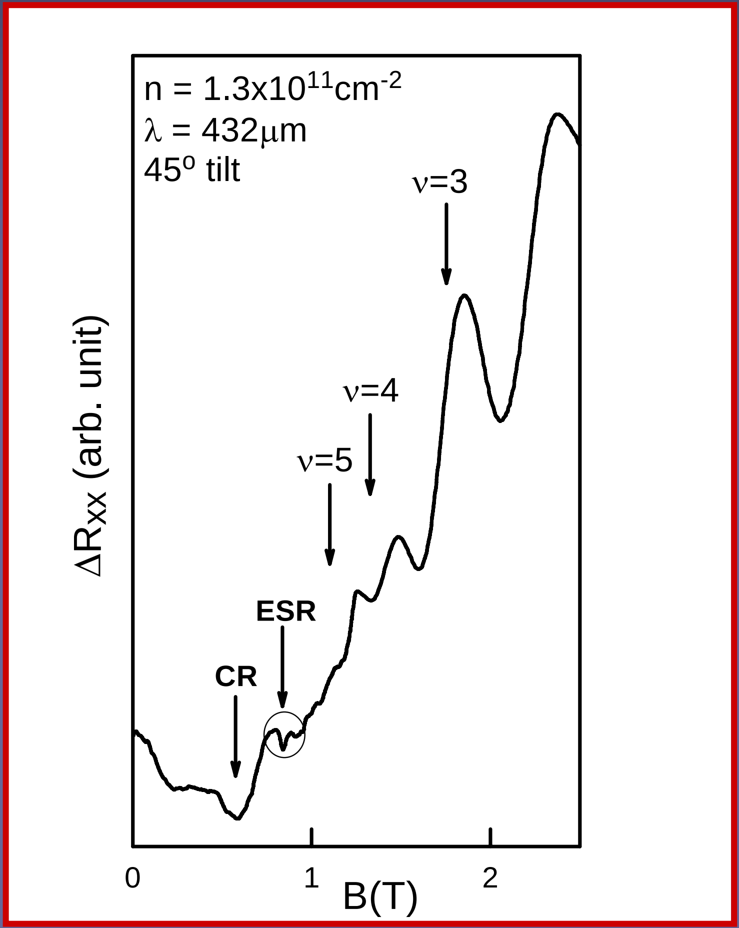
$E(k)=\hbar^2k^2/2m \pm \alpha k$

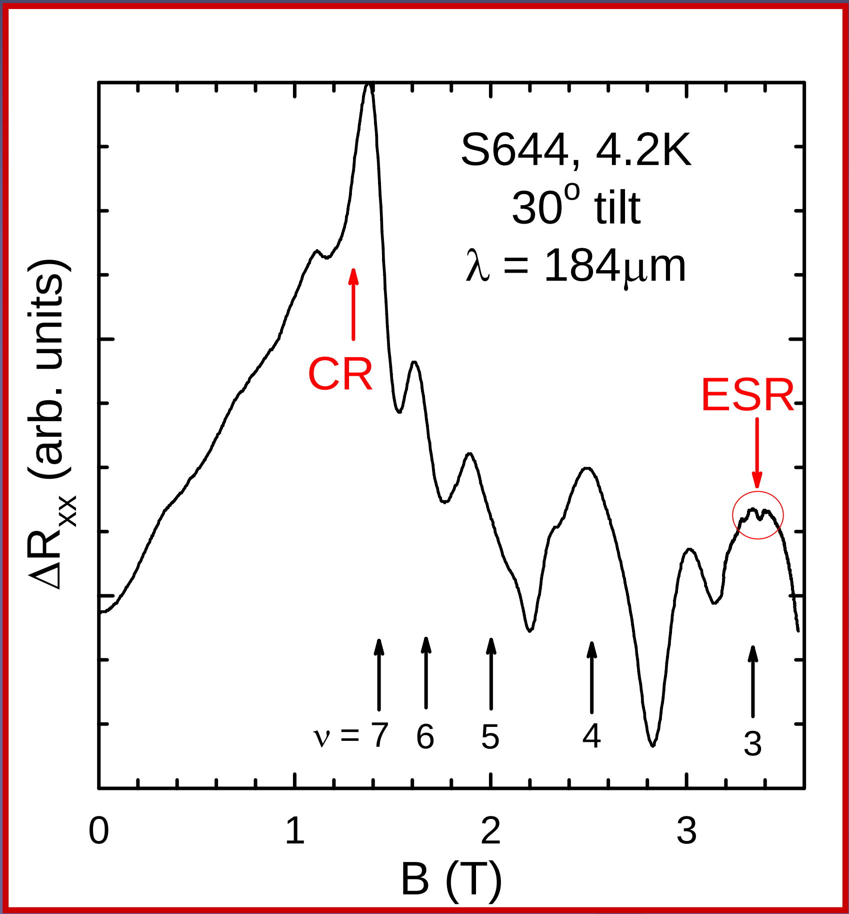
Y.A. Bychkov and E.I. Rashba, J. Phys. C **17**, 6039 (1984);
Y.A. Bychkov and E.E. Rashba, [JETP Lett. **39**, 78 (1984)]

VirginiaTech
Invent the Future
Department of Physics

**Change in g* at low magnetic field**
**G. A. Khodaparast**, *et al.* Phys. Rev. B **70**, 155322 (2004)

# Electron Spin Resonance in InSb QWs




**G. A. Khodaparast *et al.***, "Spectroscopy of Rashba spin splitting in InSb quantum wells", Phys. Rev. B **70**, 155322 (2004),

VirginiaTech
Invent the Future
Department of Physics

# Our Motivation

- To understand charge/spin dynamics in narrow gap structures
- To study phenomena such as interband and intraband photo-galvanic effects, in order to generate spin polarized current
- To probe the effect of magnetic impurities on the spin/charge dynamics

VirginiaTech
Invent the Future
Department of Physics

# Spin Relaxation Process

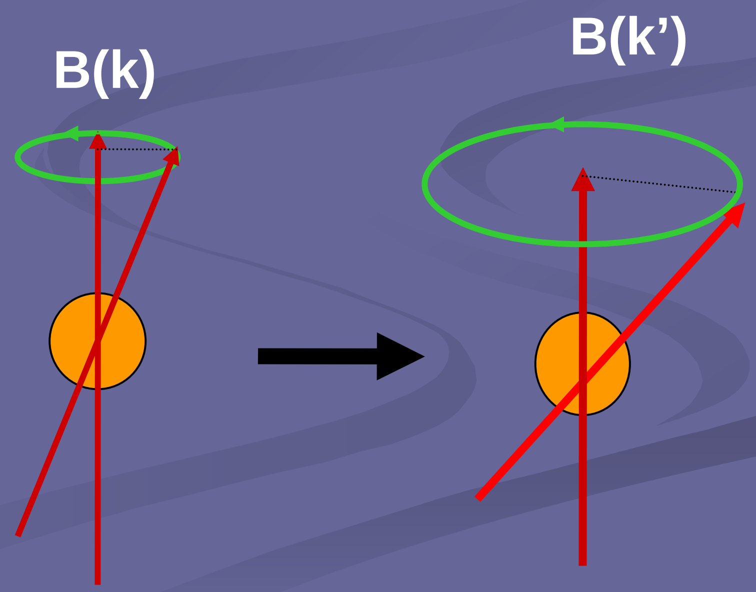
- **Elliot-Yafet Mechanism**

  Wave function of the electron is a mixture of spin up and spin down states, with a finite probability of a flip of the spin during scattering events even for spin-conserving scattering process.

- **D'yakonov-Perel Mechanism**

System acts as if in a magnetic field dependent on wavevector k

Spins precess in the field, and relax as k varies due to scattering




VirginiaTech
Invent the Future
Department of Physics

# Spin Relaxation Time [$\tau_s$]

E-Y Mechanism:

$$\frac{1}{\tau_s^{(EY)}} \approx A\alpha^2\left(\frac{E_k}{E_G}\right)^2\frac{1}{\tau_p},$$

D-P Mechanism:

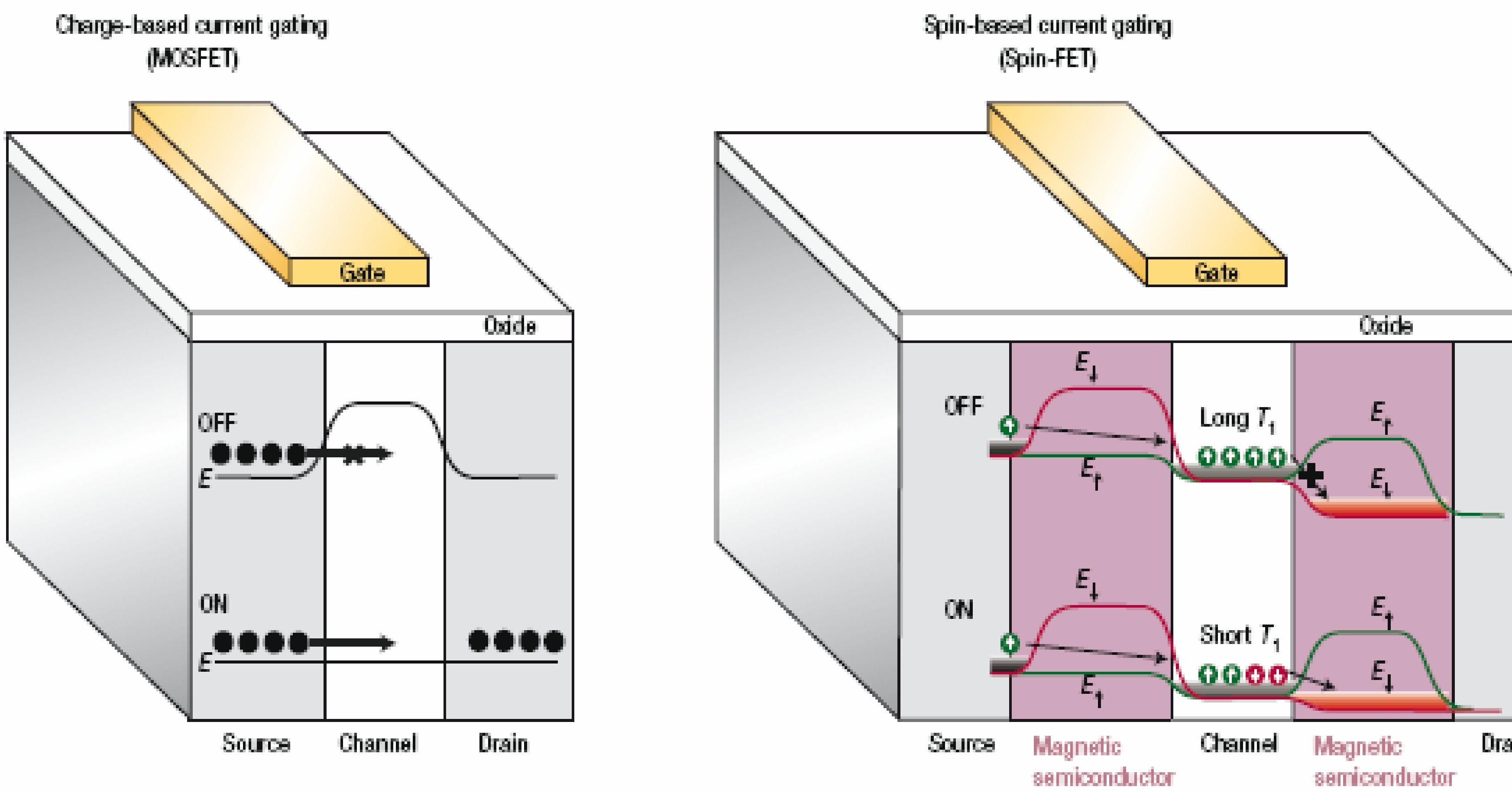
$$\frac{1}{\tau_s^{(DP)}} = Q\beta^2\frac{E_k^3}{\hbar^2 E_G}\tau_p,$$

**PRB, Volume 74,075331 2006**

$\tau_p$ => momentum relaxation time

VirginiaTech
Invent the Future
Department of Physics

# Fast or Slow Relaxation?

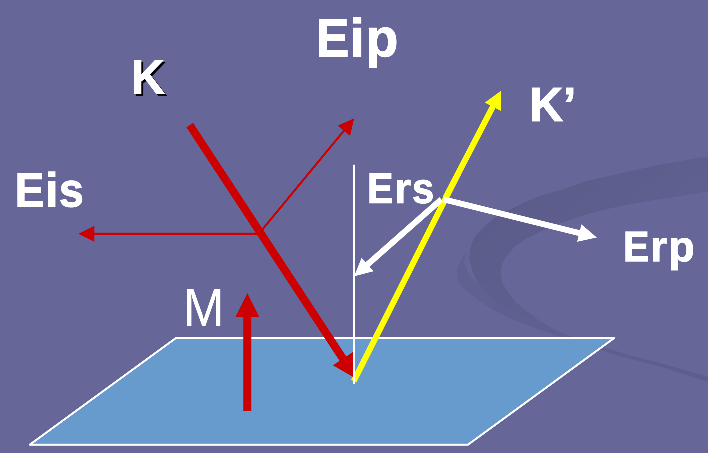



VirginiaTech
Invent the Future
Department of Physics

Kimberley Hall, Michael FLATTÉ (APL, 88, 162503 (2006)
DAVID D. AWSCHALOM AND MICHAEL E. FLATTÉ
**Nature physics | VOL 3 | MARCH 2007**

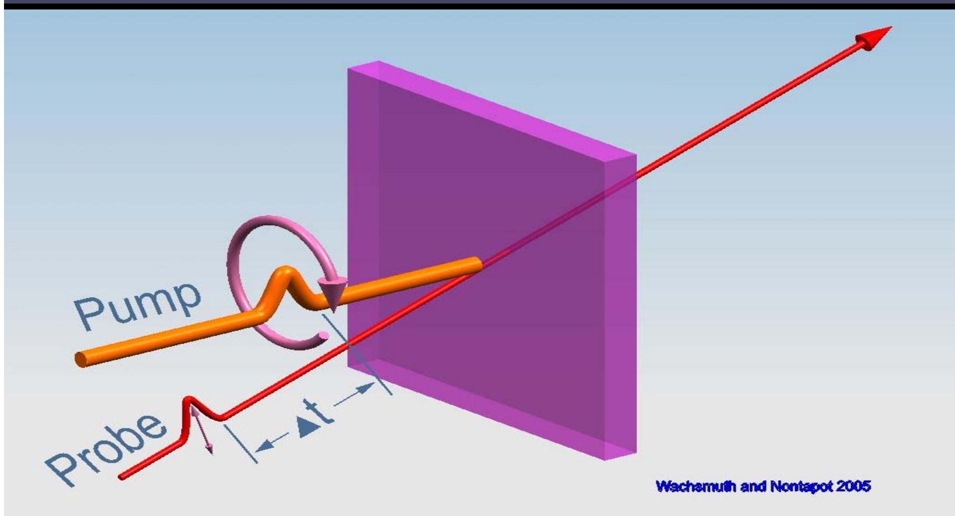
# Kerr 130 years ago !!

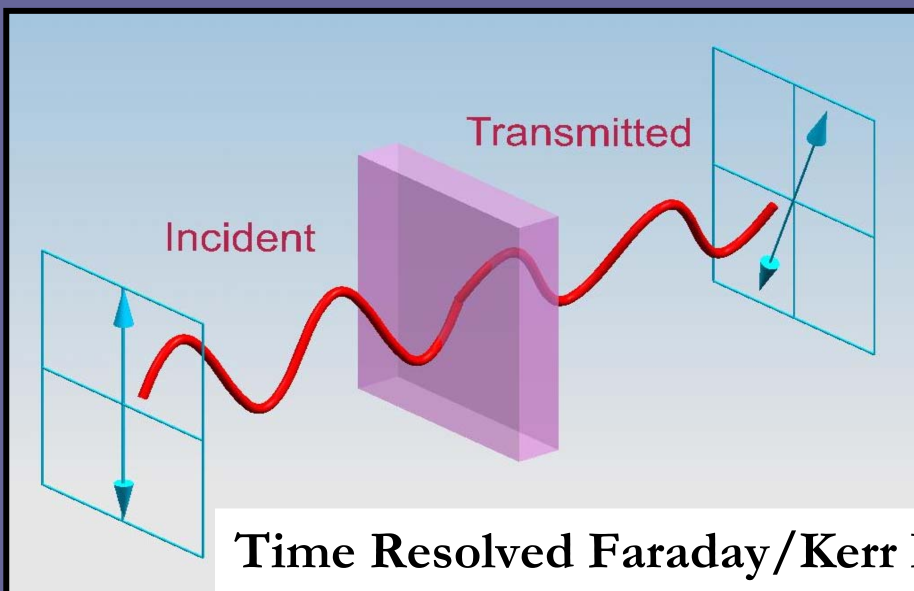
- Change in the polarization state when a  linearly polarized light reflected from a soft polished iron pole-piece of a strong electromagnet.



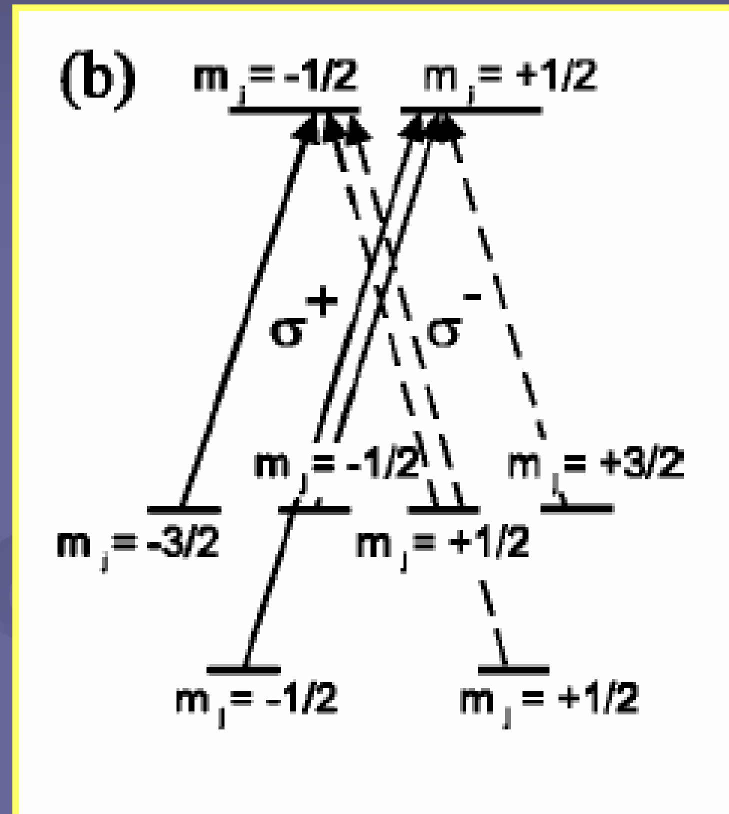

VirginiaTech
Invent the Future
Department of Physics

# Time Resolved Spectroscopy



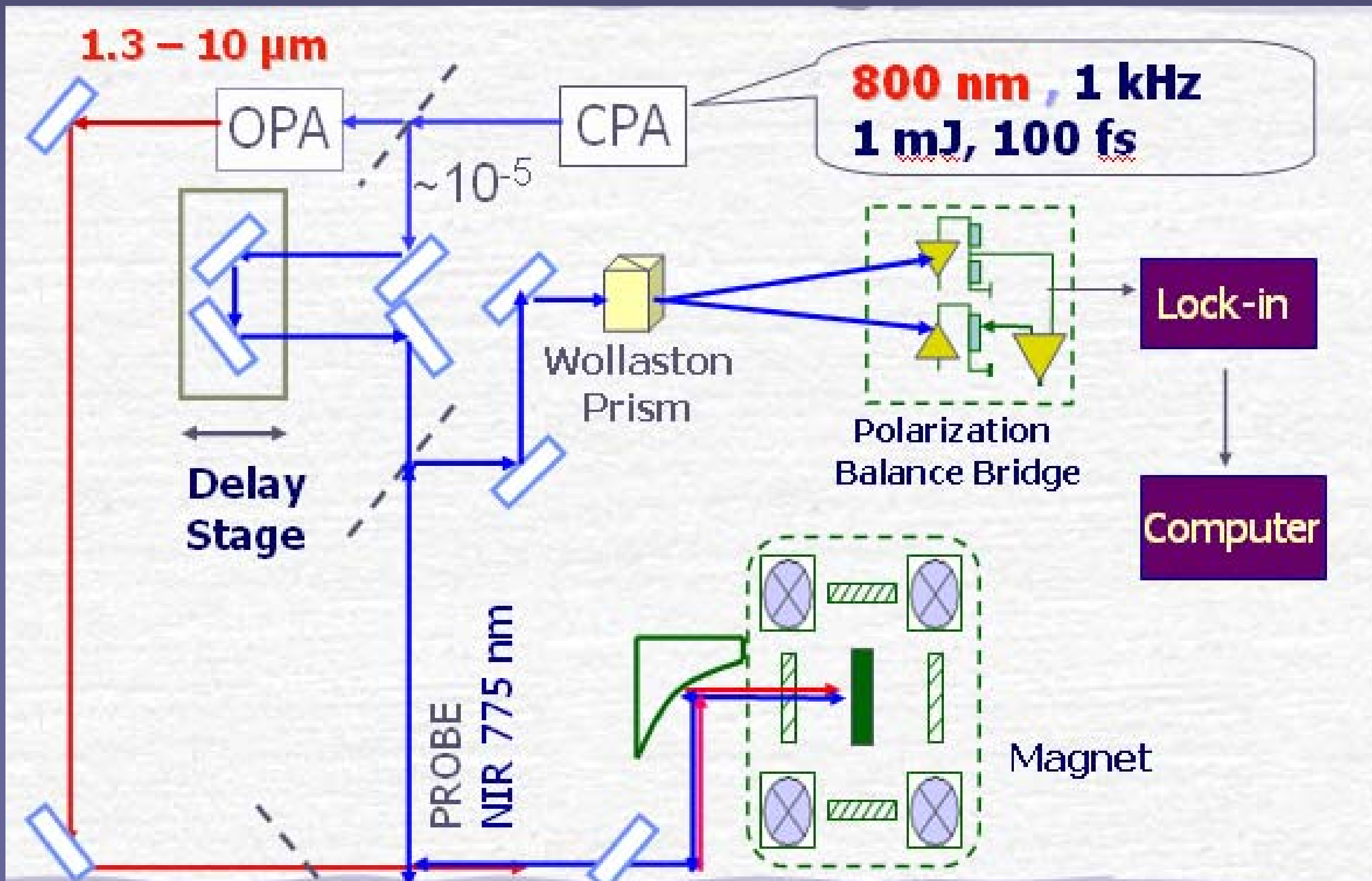




Time Resolved Faraday/Kerr Effect

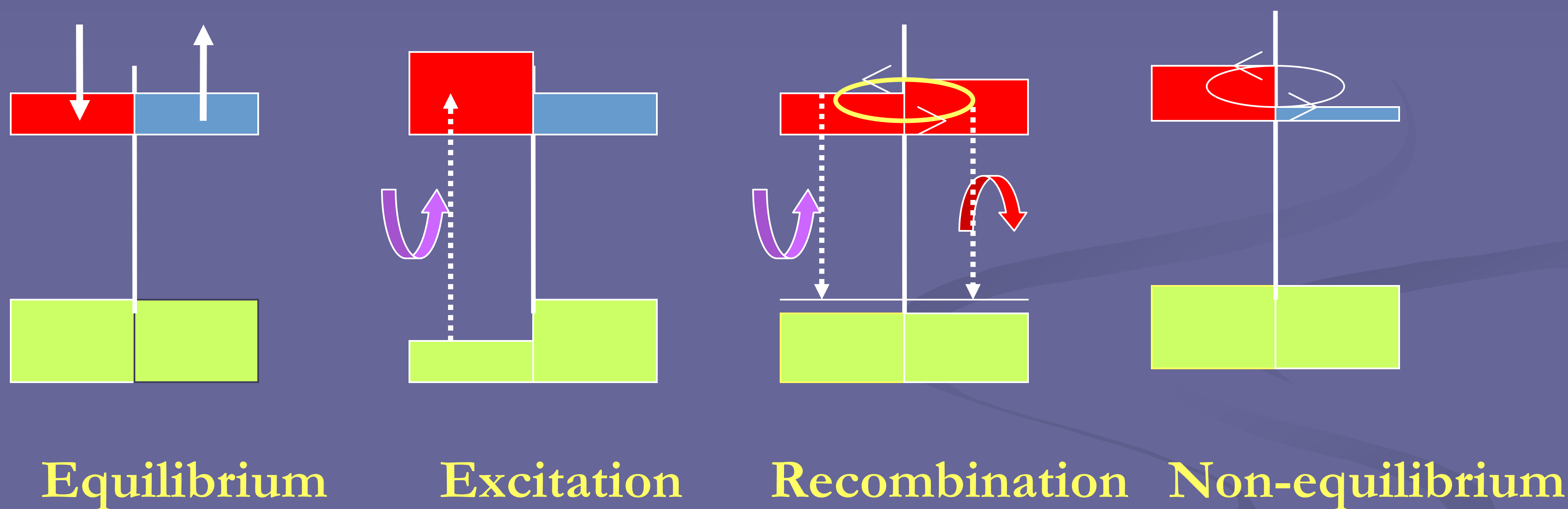



VirginiaTech
Invent the Future
Department of Physics

# Experimental Setup



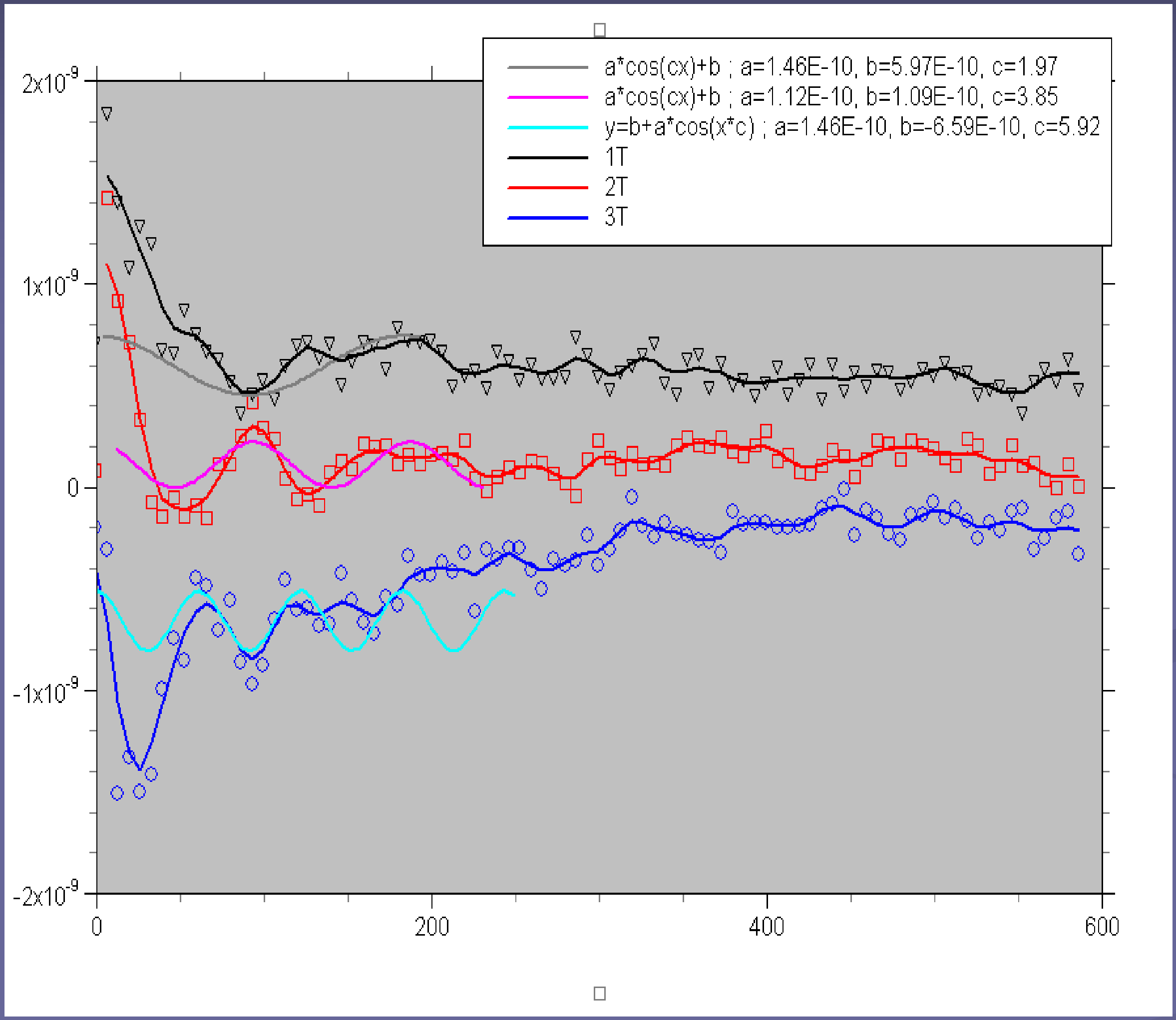
# Spin Relaxation




Virginia Tech
Invent the Future
Department of Physics

http://www.physics.ucsb.edu/~awschalom/

# Test Spin Decoherence in GaAs




We observed in GaAs but not in our narrow gap semiconductors!!

# $Al_xIn_{1-x}Sb$ Band Gap

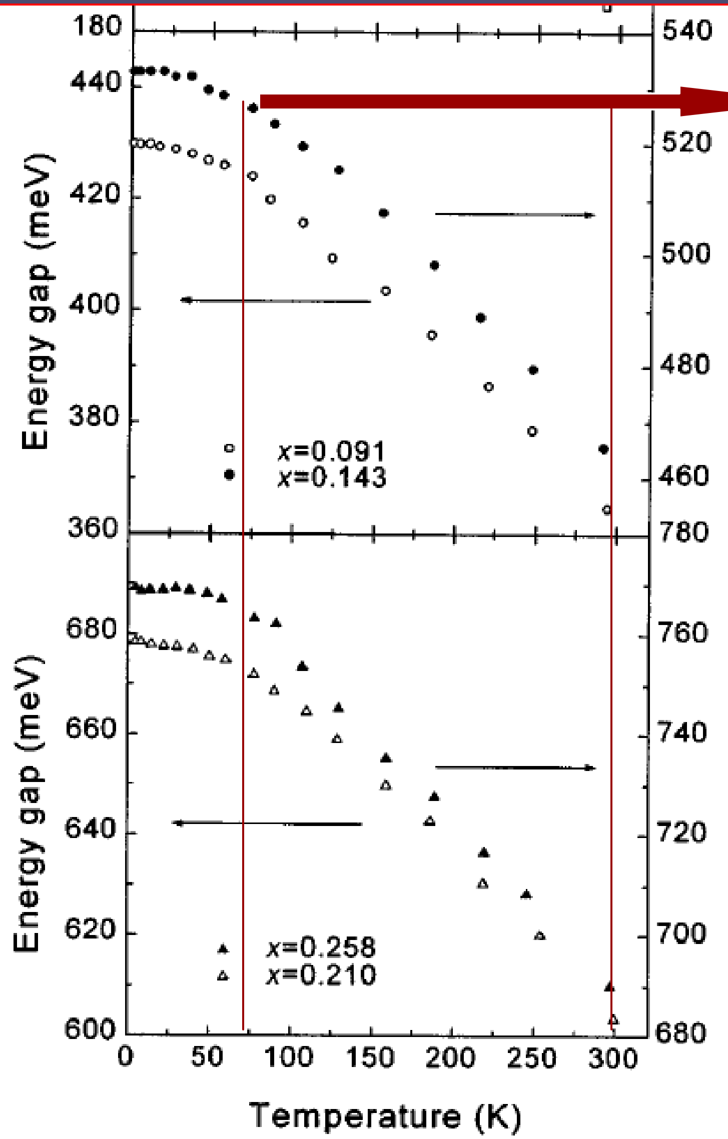
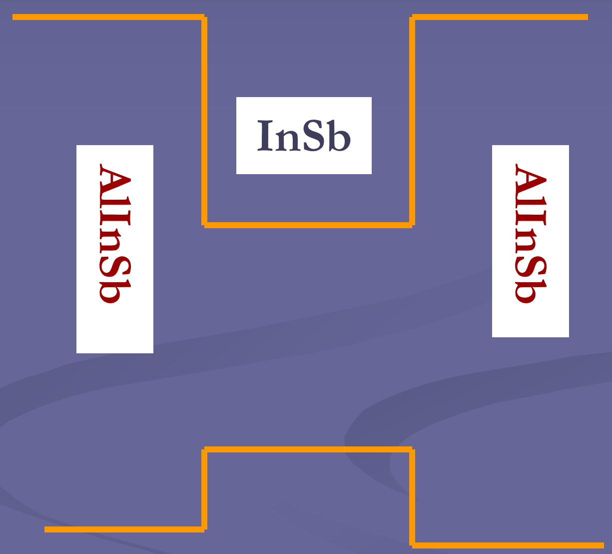



FIG. 3. Variation of $Al_xIn_{1-x}Sb$ energy gap with temperature.

77 K, ~530 meV
RT, ~470 meV

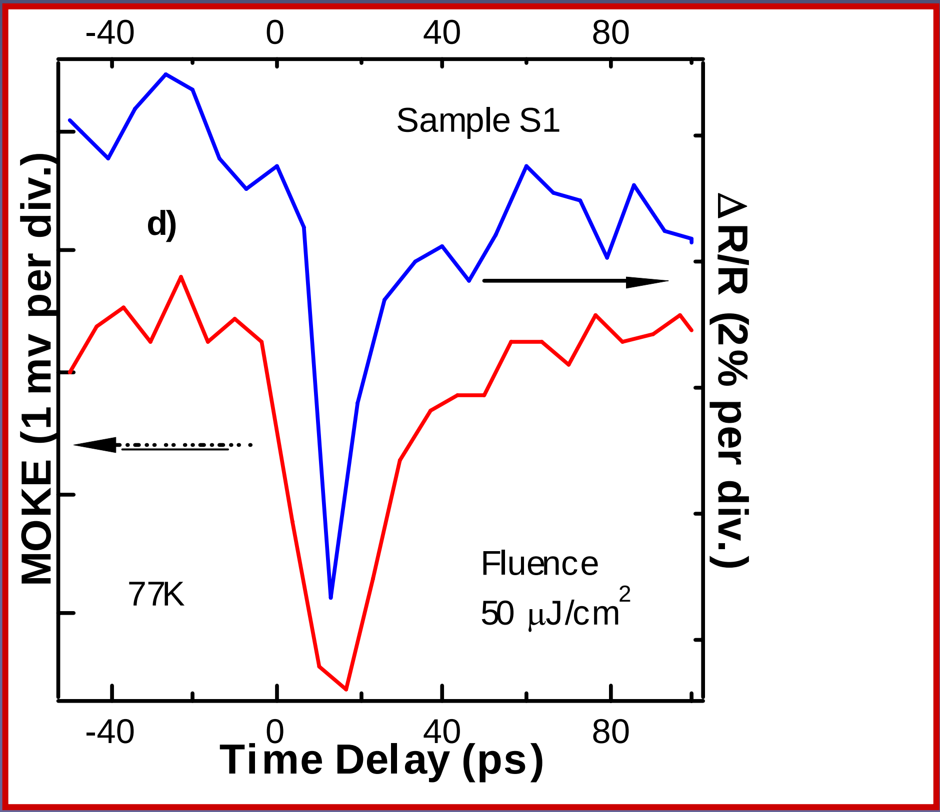
2.6 µm
477 meV




Dia *et al.* , Appl. Phys. Lett. 73, 3132 (1998)

Univ. of Oklahoma

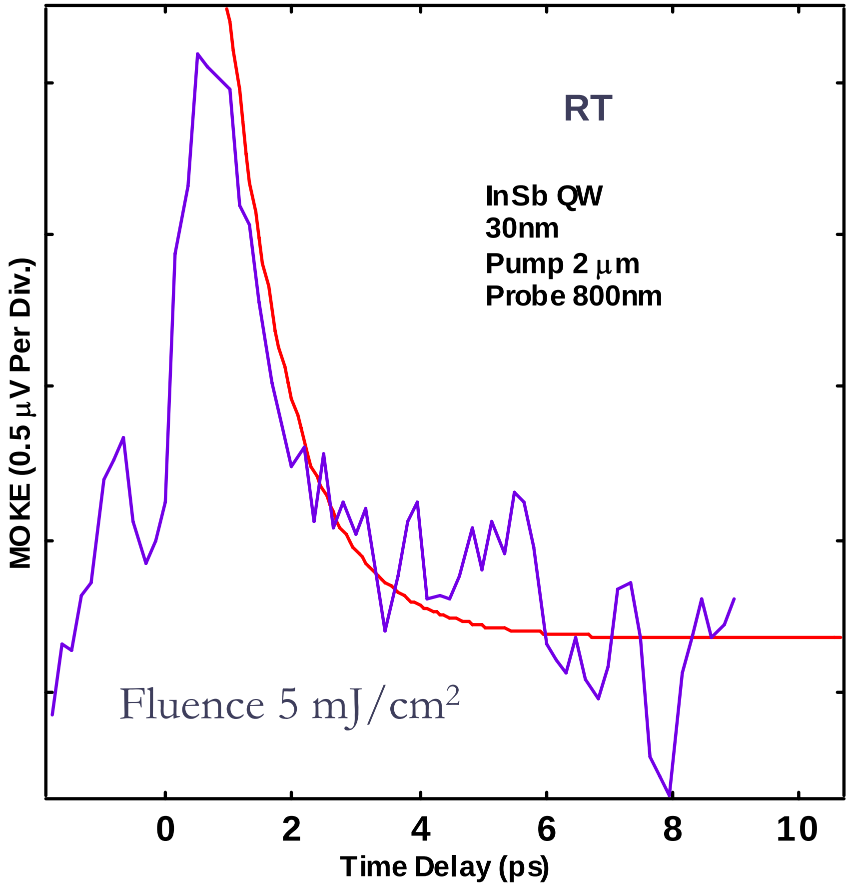
# InSb QWs Low Fluence and Degenerate

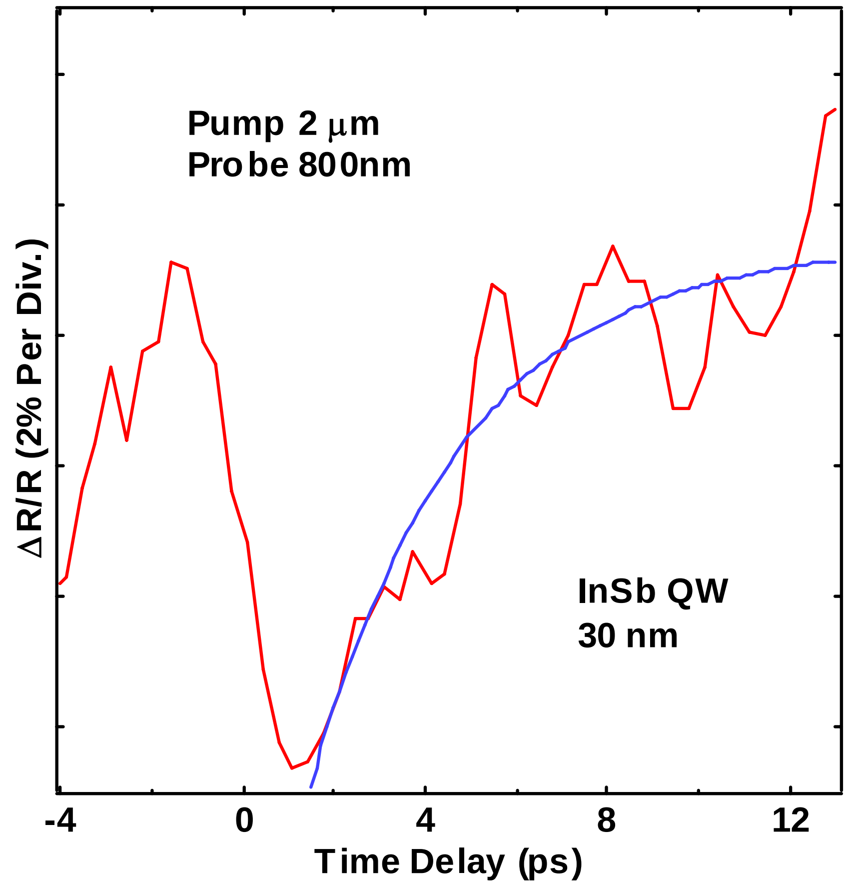



- Pump – 800 nm
- Photo-Induced Carrier density ~$10^{17}$ $cm^{-3}$

VirginiaTech
Invent the Future
Department of Physics

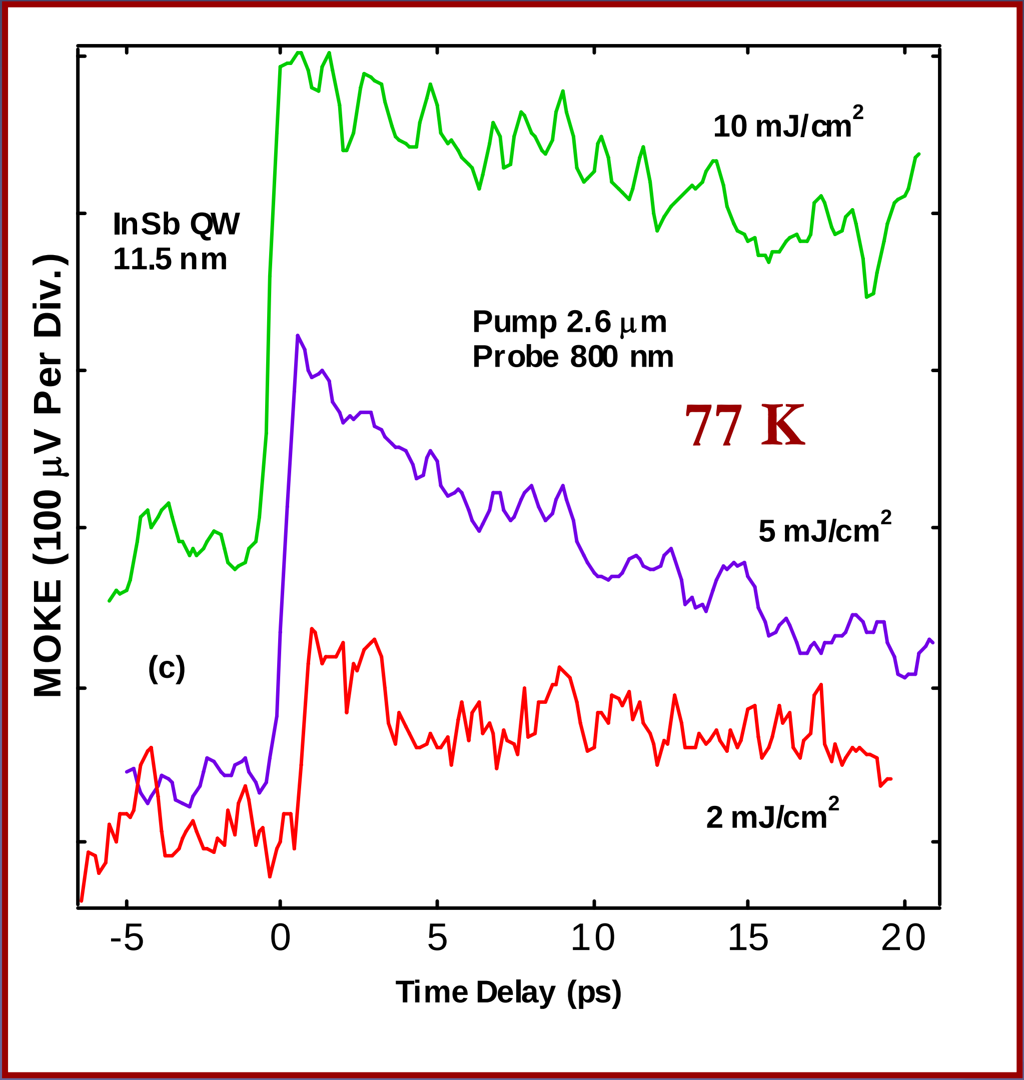
# InSb QWs, Pump 2 μm, Probe 800 nm




VirginiaTech
Invent the Future
Department of Physics

# InSb, 11.5 nm wide QW, Pump 2.6 μm, Probe 800 nm




Pumping only inside the QW

VirginiaTech
Invent the Future
Department of Physics

# Spin Relaxation in Narrow Gap Semiconductors

Boggess *et al.*, Appl. Phys., Lett., **77**, 1333 (2000).
Murzyn *et al.*, Appl. Phys., Lett., **83**, 5220(2003).
Hall *et al.*, Phys. Rev. B., **68**, 115311(2003).
Murdin *et al.*, Phys. Rev. B, **72**, 085346 (2005)
Litvinenko *et al.* , Phys. Rev. B, **74**, 075331 (2006).

For thicknesses larger than 1 microns , spin relaxations 20-50 ps
For thin InAs 0.15 micron, spin relaxation of ~ 1 ps has been reported

Litvinenko et al., ***New Journal of Physics*** **8, 49, (2006)**
In InSb QWs reported relaxations below 2 ps!!
Recent transport measurements on our InSb QW samples suggest spin coherence time of ~ 12 ps. **(Prof. Jean Heremans group at VT)**

VirginiaTech
Invent the Future
Department of Physics

# Narrow Gap Ferromagnetic Semiconductors

**Most current understanding of III-Mn-V :**

**Small lattice constants**
**Large gap and**
**Small hole effective masses**

**Such as GaMnAs**

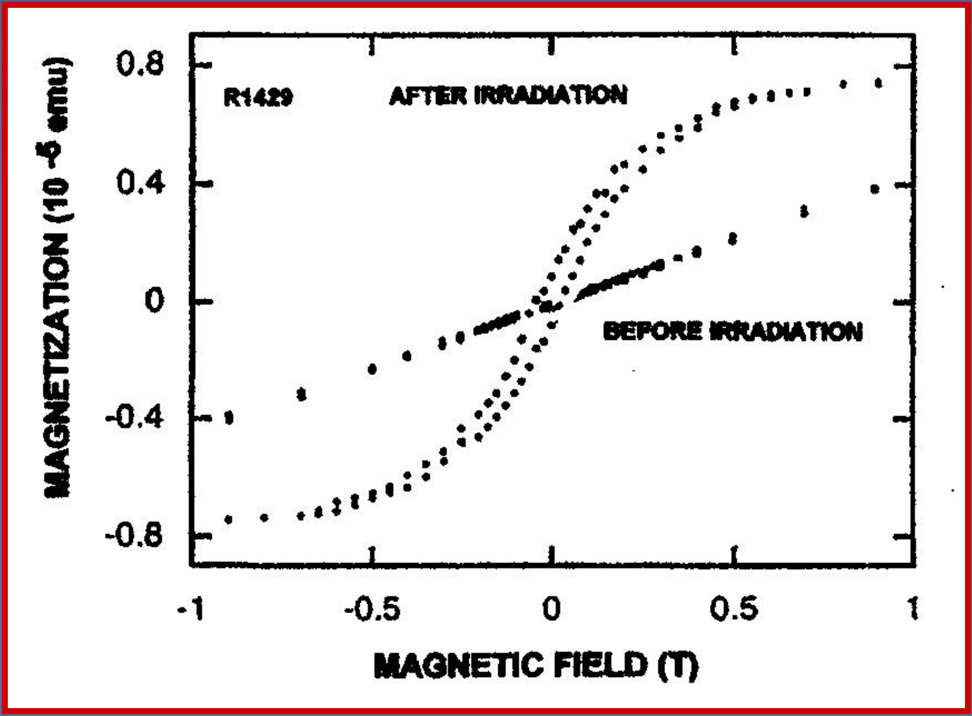
**There are observations where the photo-induced spin relaxation is influenced by Mn ions , Wang *et al.,* J. Phys.: Condens. Matter, 18, R501 (2006)**

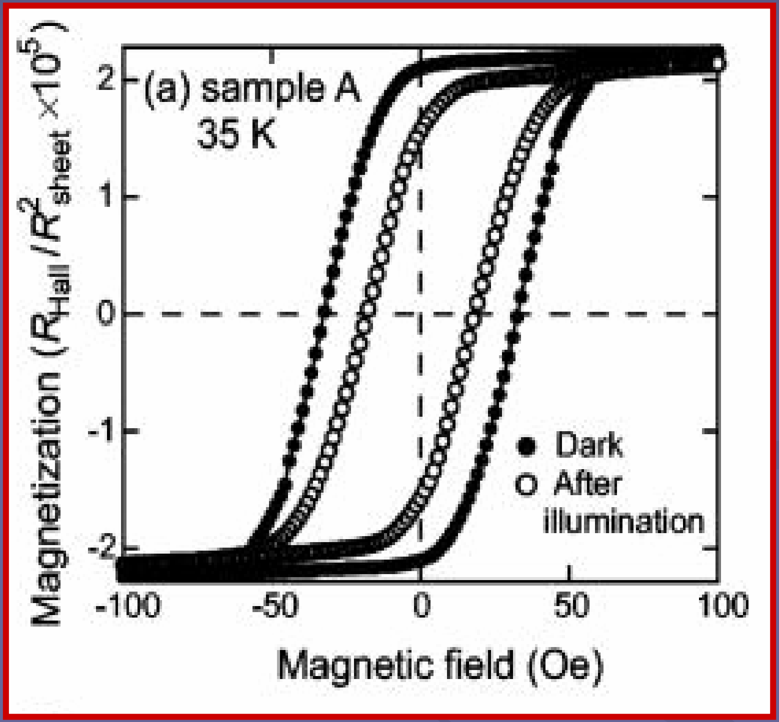
**and there are cases which no interaction has been observed, Kimel, *et al* . PRL, 92, 237203 (2004)**

VirginiaTech
Invent the Future
Department of Physics

# CW Optical Control of Ferromagnetism

**S. Koshihara *et al*., PRL 78, 4617 (1997); A. Oiwa *et al*., APL 78, 518 (2001).**




- Light-induced ferromagnetism
- Light-induced coercivity decrease

VirginiaTech
Invent the Future
Department of Physics

# InMnSb Films

Mn Content 2.0-2.8%, p~ $2\times10^{20}$ $cm^{-3}$, $\mu$ ~ 100 $cm^2/Vs$

**Tc= 10K**

**InMnSb (0.23 μm)**

**InSb buffer layer (0.1 μm)**

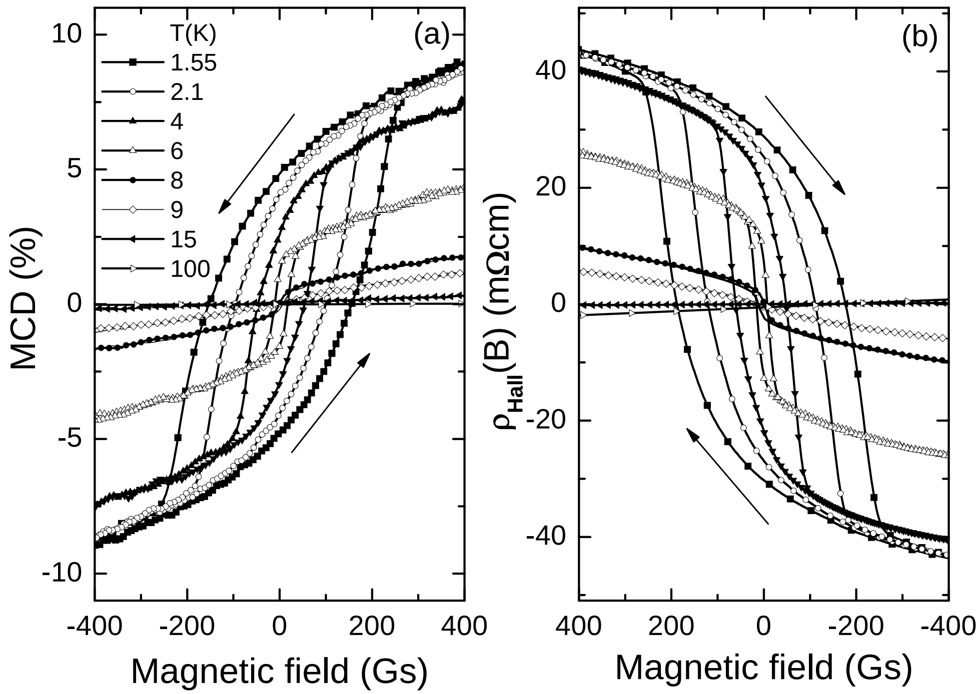
**CdTe substrate (4.5 μm)**

**GaAs substrate**

T.Wojtowicz, X. Liu, J.K Furdyna, University of Notre Dame

VirginiaTech
Invent the Future
Department of Physics

# InMnSb Based Ferromagnetic Structures



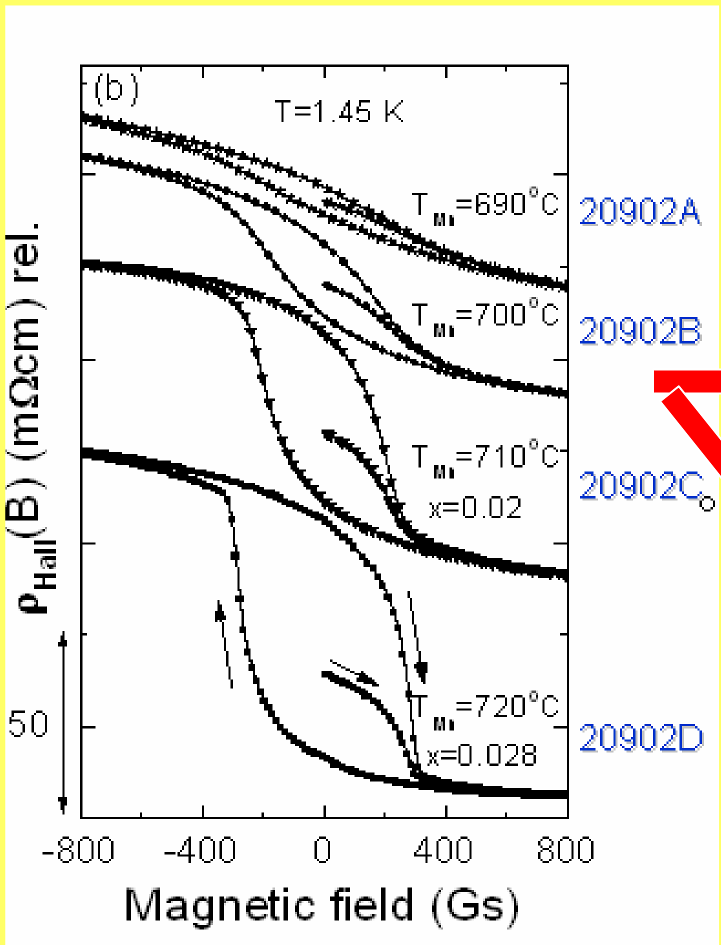

- Negative $R_A$, not expected for a p-type structure
- $R_A$ positive in GaMnAs,InMnAs negative in GaMnSb, not fully understood

Wojtowicz T, **Appl. Phys. Lett**. 82**,** 4310, 2003
Wojtowicz T, **Physica E20**, 325, 2004

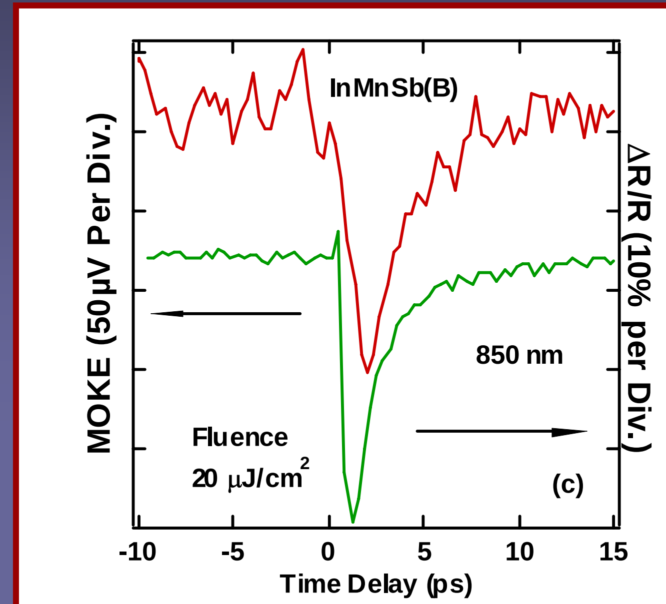
Large spin-orbit coupling

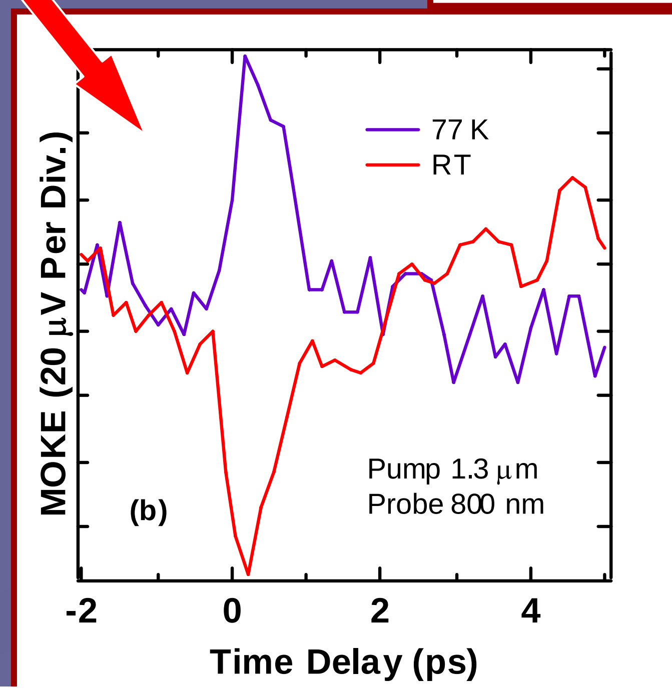
VirginiaTech
Invent the Future
Department of Physics

# Fluence Dependence of Relaxation Times




Fluence
20 μJ/cm²
Photo-induced
$10^{17}$ cm$^{-2}$

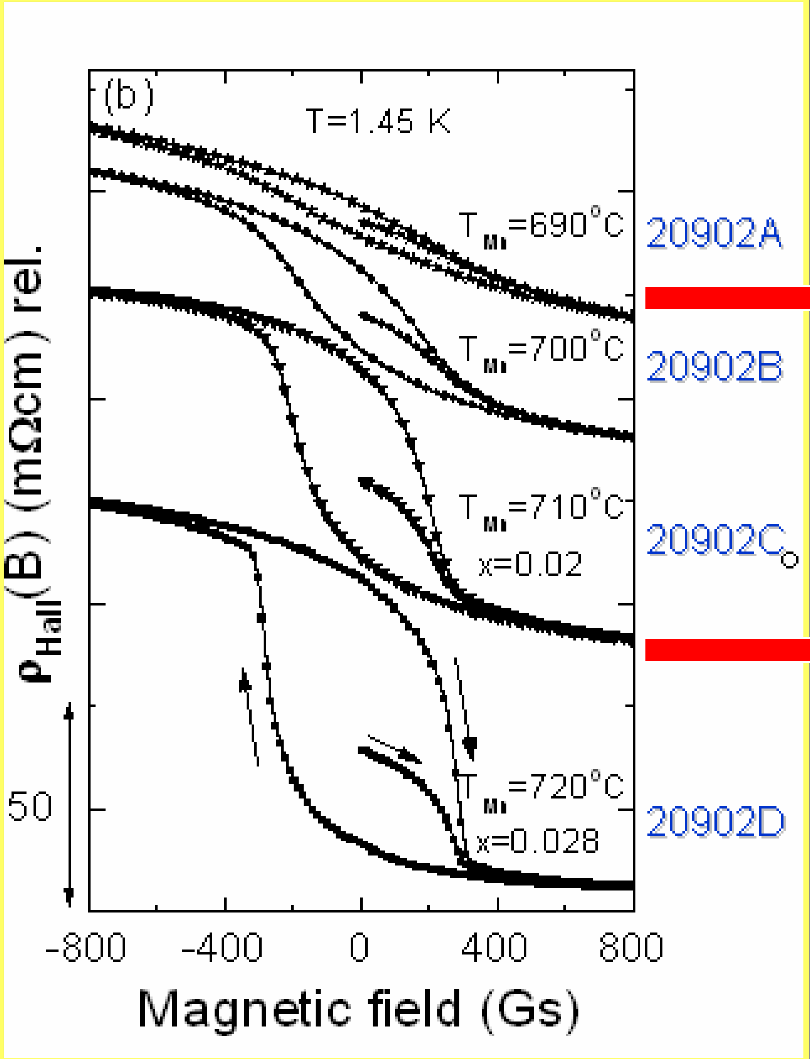


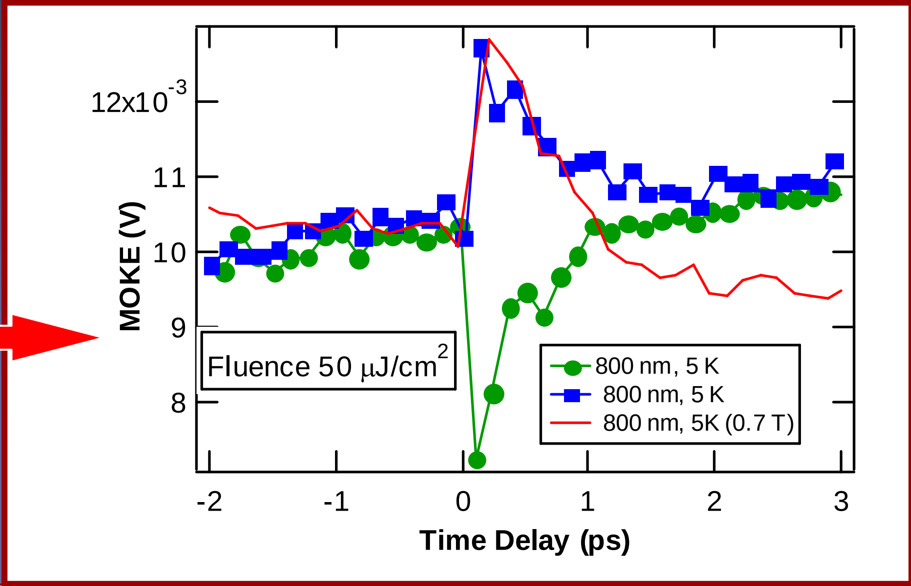



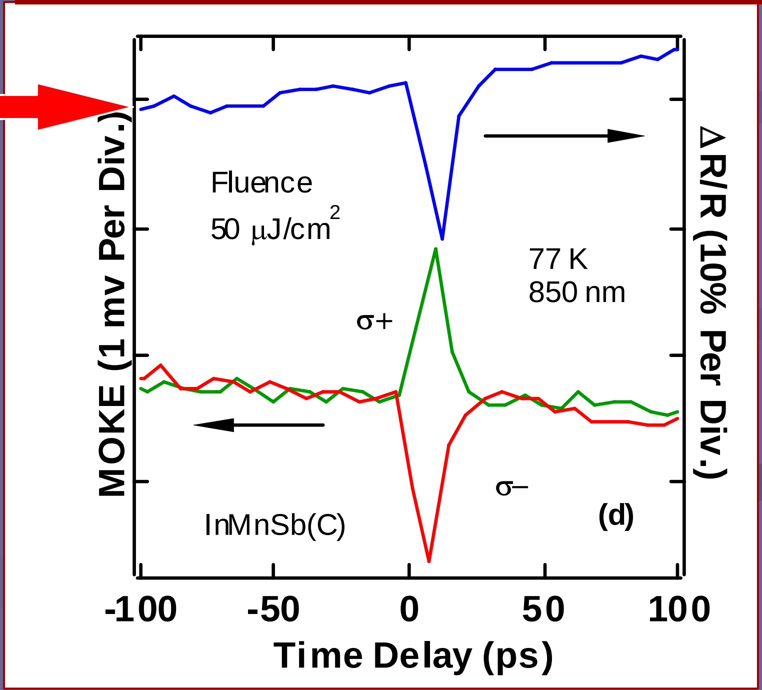

Fluence
5 mJ/cm²
Photo-induced
$10^{19}$ cm$^{-2}$

VirginiaTech
Invent the Future
Department of Physics

# InMnSb Samples, Different Mn Effusion Cell Temp

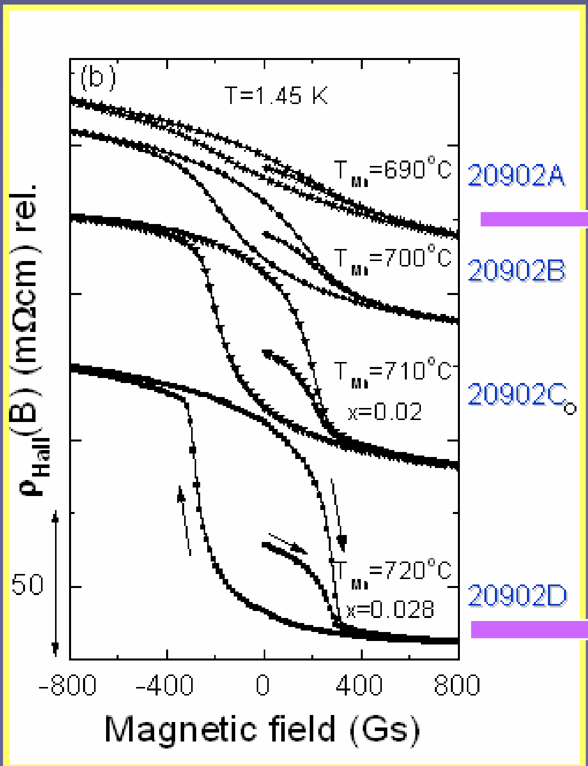


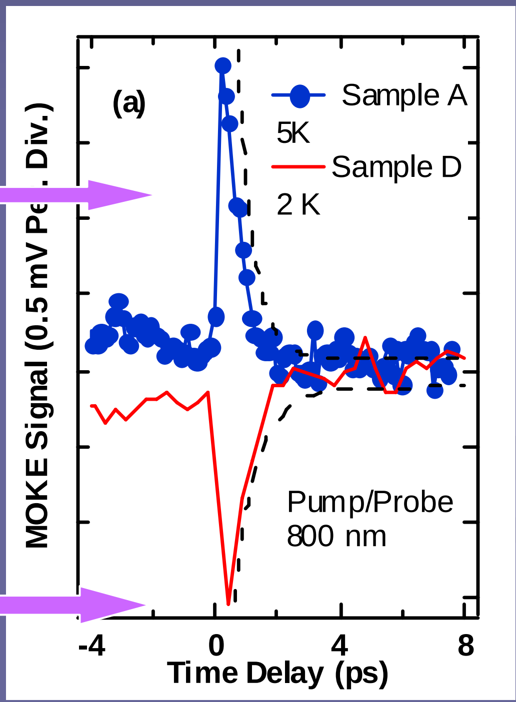



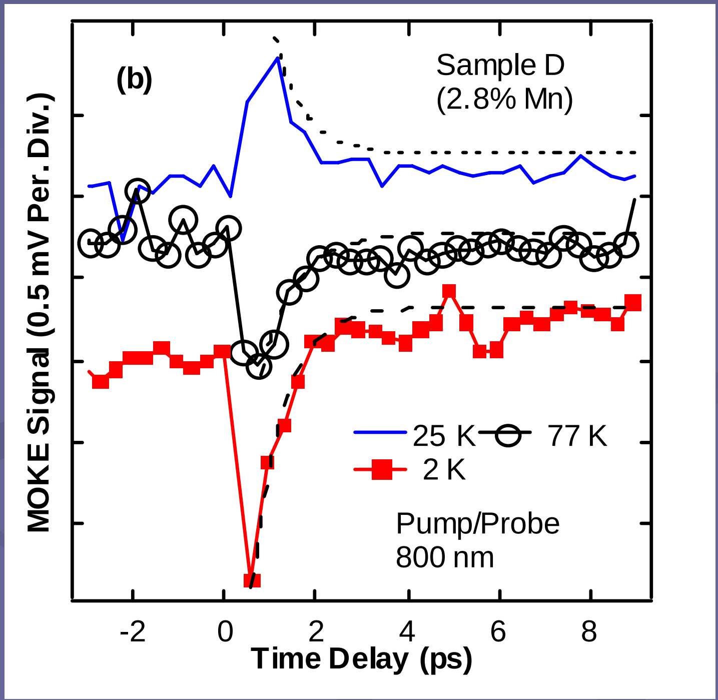




VirginiaTech
Invent the Future
Department of Physics

# Temperature Dependence of InMnSb



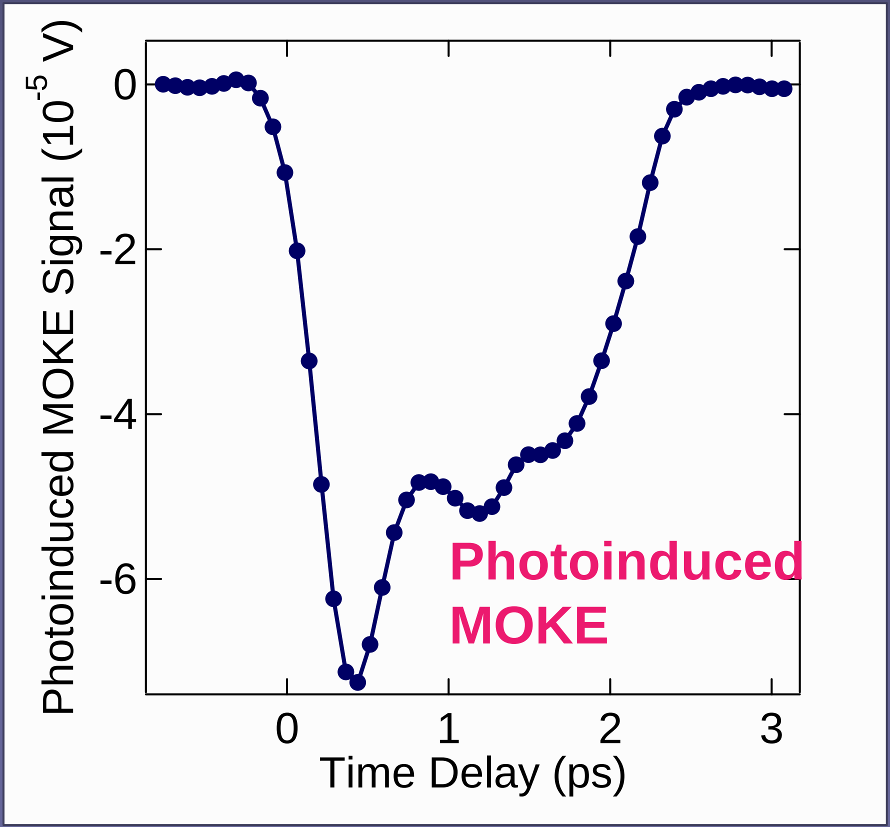



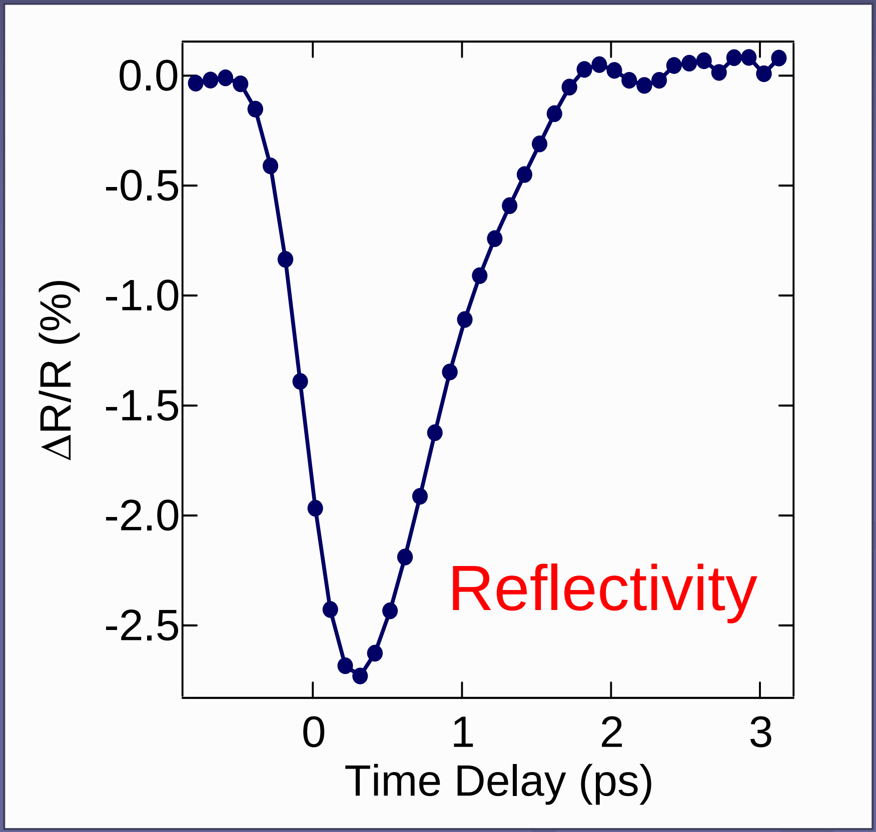




VirginiaTech
Invent the Future
Department of Physics

K. Nontapot *et al.*, APL, 90, 143109 (2007)

# Dynamics in InMnAs




J. Wang J, G. A. Khodaparast, J. Kono, T. Slupinski, A. Oiwa, and H. Munekata
Journal of Modern Optics 51, 2771,2004

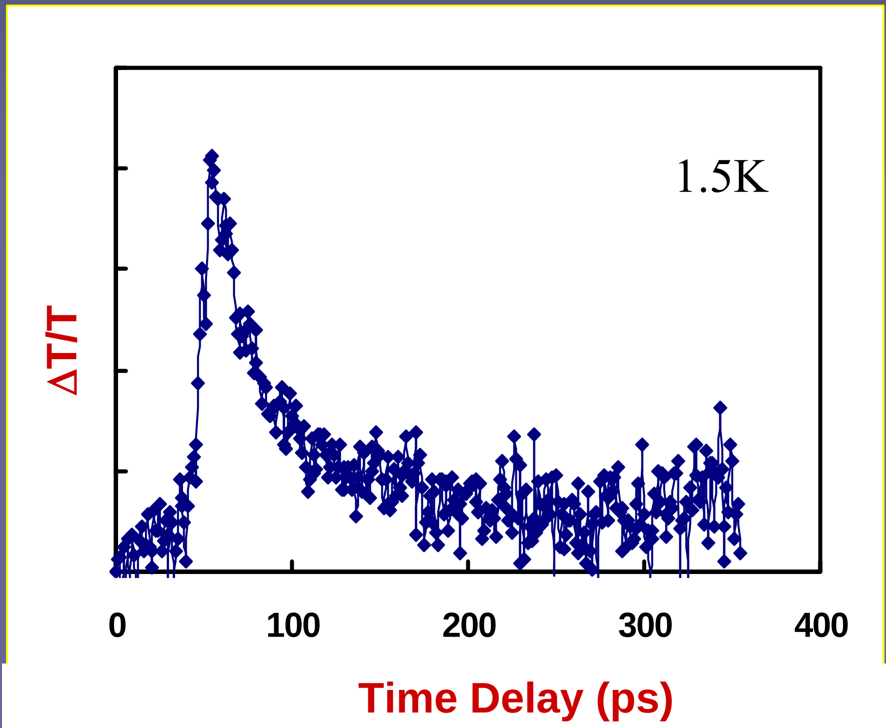
# Summary/Future Plans

- We have explored spin/charge dynamics in a series of Narrow Gap Semiconductors
- We can alter the relaxation as a function of photo-induced
- The relaxations in ferromagnetic samples very much depends on the sample properties

Working on spin-polarized current generation
Fabricating 1-D system to probe the dynamics in lower dimensions
Taking advantages of the FEL to probe the conduction bands

VirginiaTech
Invent the Future
Department of Physics

# Inter subband Dynamics




Differential Transmission

Interband Pumping (800 nm)

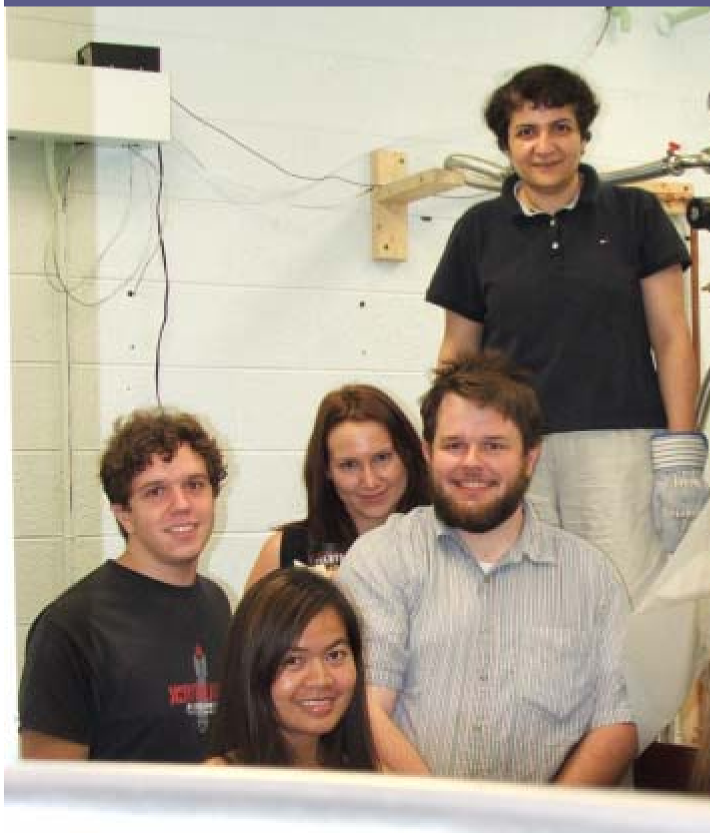
Probe Beam (42 μm)

Undoped InSb MQW containing 25 periods of 35 nm InSb wells

VirginiaTech
Invent the Future
Department of Physics

# Group Members

**Brett, Emily, Kanokwan, Matt, Rajeev**



Jonathan and Ashley

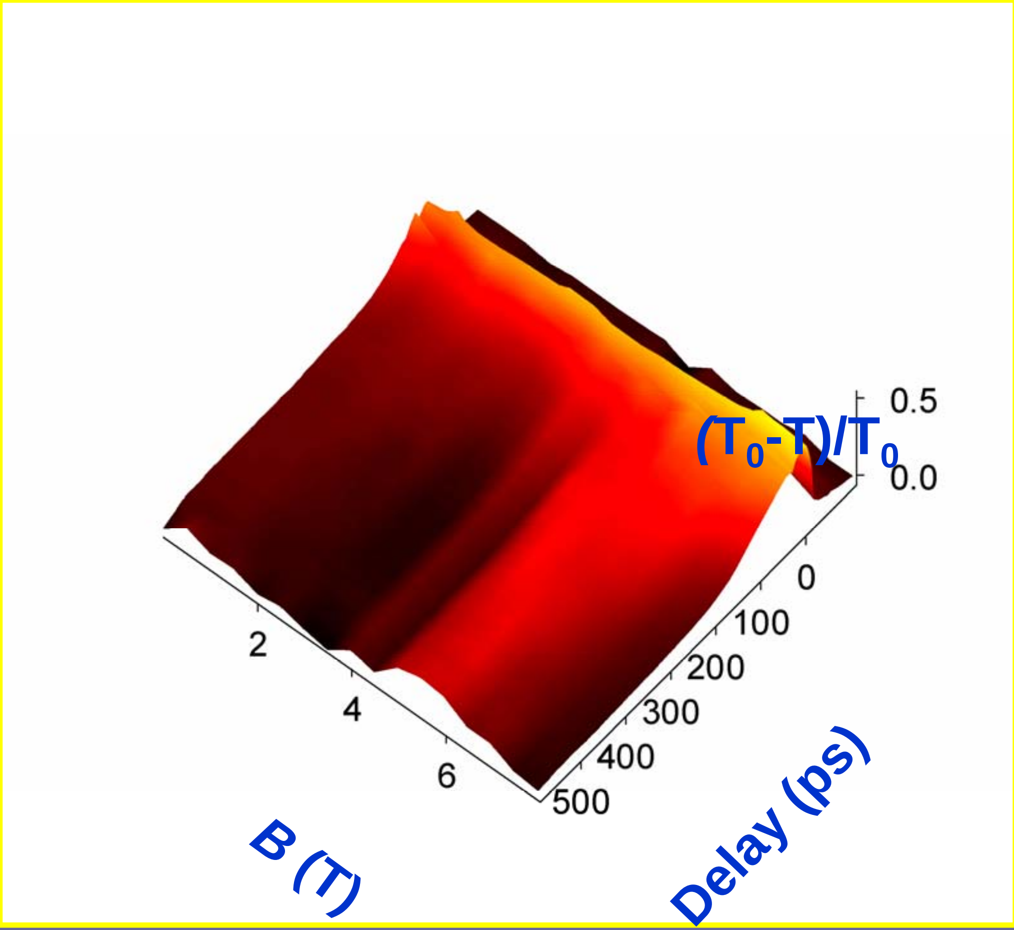
VirginiaTech
Invent the Future
Department of Physics

Thank you for your attention

VirginiaTech
Invent the Future

Department of Physics

# Time Resolved Cyclotron Measurements




Interband pump + Intraband probe

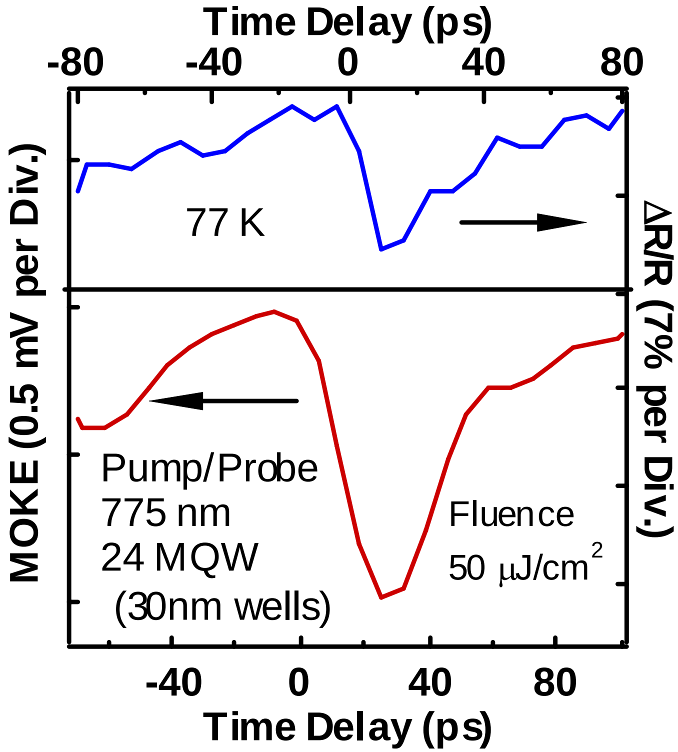
Monitor dynamics of relaxing carriers in conduction band directly in time:

| | |
|---|---|
| Effective mass | m*(t) |
| Density | n(t) |
| Scattering time | τ(t) |

VirginiaTech
Invent the Future
Department of Physics

G. A. Khodaparast *et al*, PRB 67 035307 (2003)

# Relaxations in Undoped InSb QW




- Photo-Induced Carrier density ~$10^{17}$ $cm^{-3}$
- Carrier/Spin lifetime longer than 40ps

Undoped InSb MQW containing 25 periods of 30 nm InSb wells

VirginiaTech
Invent the Future
Department of Physics