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

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InSb Based Samples

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III-V Semiconductors
# InSb Quantum Wells

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>InSb cap</td>
<td>100Å</td>
</tr>
<tr>
<td>$\text{Al}<em>x\text{In}</em>{1-x}\text{Sb}$ Top Layer</td>
<td>100Å</td>
</tr>
<tr>
<td>$\text{Al}<em>x\text{In}</em>{1-x}\text{Sb}$ Spacer</td>
<td>1000Å</td>
</tr>
<tr>
<td>$\text{Al}<em>x\text{In}</em>{1-x}\text{Sb}$ Barrier</td>
<td>300Å</td>
</tr>
<tr>
<td>InSb Well</td>
<td>11.5 nm to 30nm</td>
</tr>
<tr>
<td>$\text{Al}<em>x\text{In}</em>{1-x}\text{Sb}$ Barrier</td>
<td>300Å</td>
</tr>
<tr>
<td>$\text{Al}<em>x\text{In}</em>{1-x}\text{Sb}$ Layer</td>
<td>600Å</td>
</tr>
<tr>
<td>$\text{Al}<em>x\text{In}</em>{1-x}\text{Sb}$ Buffer</td>
<td>4μm</td>
</tr>
<tr>
<td>AlSb Buffer</td>
<td>2150Å</td>
</tr>
<tr>
<td>GaAs (001) substrate</td>
<td></td>
</tr>
</tbody>
</table>

- Density: $1-4 \times 10^{11}$ 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)

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

<table>
<thead>
<tr>
<th>Material</th>
<th>( m^*/m_0 )</th>
<th>g-factor</th>
<th>( E(k) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaAs</td>
<td>0.067</td>
<td>-0.5</td>
<td>Least non-parabolic</td>
</tr>
<tr>
<td>InAs</td>
<td>0.023</td>
<td>-15</td>
<td>More non-parabolic</td>
</tr>
<tr>
<td>InSb</td>
<td>0.014</td>
<td>-51</td>
<td>Most non-parabolic</td>
</tr>
</tbody>
</table>
InSb Based Heterostructures

An ideal model of a narrow-gap semiconductor

- Small effective mass, large g-factor
- Large spin-orbit coupling
- Small e-e interaction
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 not insulating at \( \nu < 1 \)


Ballistic transport in InSb mesoscopic structures
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!

Narrow Gap: Revisited

Normal Field Effective Transistor (FET)


Spin Polarized FET

$V_G$

$\text{I}_{SD}$
InSb Quantum Well Structures

Symmetric quantum well

Asymmetric quantum well

$\text{Beff} = E \times \frac{V}{c}$
Zero Field Spin Splitting

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

Bulk Inversion asymmetry is known as → Dresselhaus effect

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

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

(a) (b)

Rashba Splitting at $B>0$

\[ E(k) = \frac{\hbar^2 k^2}{2m} \pm \alpha k \]

In addition to:


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)]

Change in $g^*$ at low magnetic field
Electron Spin Resonance in InSb QWs

Our Motivation

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

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

$\tau_p$ => momentum relaxation time

PRB, Volume 74, 075331 2006
Fast or Slow Relaxation?

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.
Time Resolved Spectroscopy

Time Resolved Faraday/Kerr Effect
Experimental Setup

OPA

CPA

Wollaston Prism

Delay Stage

PROBE NIR 775 nm

Magnet

Polarization Balance Bridge

Lock-in

Computer

1.3 - 10 μm

800 nm, 1 kHz
1 mJ, 100 fs

~10⁻⁵
Spin Relaxation

Equilibrium  Excitation  Recombination  Non-equilibrium

http://www.physics.ucsb.edu/~awschalom/
We observed in GaAs but not in our narrow gap semiconductors!!
Al$_x$In$_{1-x}$Sb Band Gap

77 K, $\sim$530 meV
RT, $\sim$470 meV

2.6 $\mu$m
477 meV

Dia et al., Appl. Phys. Lett. 73, 3132 (1998)
Univ. of Oklahoma

FIG. 3. Variation of Al$_x$In$_{1-x}$Sb energy gap with temperature.
InSb QWs Low Fluence and Degenerate

- Pump – 800 nm
- Photo-Induced Carrier density $\sim 10^{17} \text{ cm}^{-3}$
InSb QWs, Pump 2 µm, Probe 800 nm

RT

InSb QW
30 nm
Pump 2 µm
Probe 800 nm

Fluence 5 mJ/cm²

MOKE (0.5 µV Per Div.)

Time Delay (ps)

ΔR/R (2% Per Div.)

Pump 2 µm
Probe 800nm

InSb QW
30 nm

Time Delay (ps)
InSb, 11.5 nm wide QW, Pump 2.6 μm, Probe 800 nm

MOKE (100 μV Per Div.)

Pumping only inside the QW

77 K
Spin Relaxation in Narrow Gap Semiconductors


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

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)*
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)
CW Optical Control of Ferromagnetism


- Light-induced ferromagnetism
- Light-induced coercivity decrease
InMnSb Films

Mn Content 2.0-2.8%, p~ 2x10^{20} \text{ cm}^{-3}, \mu \sim 100 \text{ cm}^{2}/\text{Vs}

T_c = 10K

- InMnSb (0.23 \mu m)
- InSb buffer layer (0.1 \mu m)
- CdTe substrate (4.5 \mu m)
- GaAs substrate

T. Wojtowicz, X. Liu, J.K Furdyna, University of Notre Dame
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
Fluence Dependence of Relaxation Times

Fluence 20 μJ/cm²
Photo-induced 10¹⁷ cm⁻²

Fluence 5 mJ/cm²
Photo-induced 10¹⁹ cm⁻²
InMnSb Samples, Different Mn Effusion Cell Temp

MOKE (1 mV Per Div.)

-1 0 0.5 1.0

Time Delay (ps)

MOKE (V)

3 2 1 0 -1 -2

Time Delay (ps)

Fluence 50 μJ/cm²

-2 -1 0 1 2 3

Time Delay (ps)

Fluence 50 μJ/cm²

-100 -50 0 50 100

Time Delay (ps)

ΔR/R (10% Per Div.)

77 K 850 nm

σ+

σ−
Temperature Dependence of InMnSb

K. Nontapot et al., APL, 90, 143109 (2007)
Dynamics in InMnAs

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
Inter subband Dynamics

Differential Transmission
Interband Pumping (800 nm)
Probe Beam (42 μm)

Undoped InSb MQW containing 25 periods of 35 nm InSb wells
Group Members

Brett, Emily, Kanokwan, Matt, Rajeev

Jonathan and Ashley
Thank you for your attention
Interband pump + Intraband probe

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

- Effective mass: $m^*(t)$
- Density: $n(t)$
- Scattering time: $\tau(t)$
Relaxations in Undoped InSb QW

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

Undoped InSb MQW containing 25 periods of 30 nm InSb wells