Optical Control in Semiconductors for Spintronics and Quantum Information Processing

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Our Spin/Q.I.P. Team

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Miniaturization – approaching a physical limit
Quantum effects – statistical, fuzzy, strange – unavoidable
Novel **quantum technologies** being sought → better performance and new functionality and multi-functionality
**Spin-based** electronics, quantum electronics based on quantum coherence, interference, and entanglement, … etc.

“Quantum physics holds the key to the further advance of computing in the postsilicon era.”
- J. Birnbaum and R. S. Williams

“Coherent spin packets may offer genuine quantum devices through their wave-like properties.”
- D. D. Awschalom
Outline

- Semiconductor ‘Spintronics’
- Towards Solid-State Realization of Quantum Information Processing
- Our Approach: Ultrafast Optical Control
- Our Recent Discoveries
  - Ultrafast Photoinduced Softening (UPS) in a Ferromagnetic Semiconductor
  - Ultrafast Photoinduced Transparency (UPT) using the Dynamic Franz-Keldysh Effect (DFKE)
- Summary
Emerging Technologies for Solid-State Information Processing

Use *discrete, quantized degrees* of freedom in a physical device to *perform information processing* functions.

**Spintronics**
- Use *spins* in solid state devices
- Improve information processing
- Add new functionalities

**Quantum Information Processing**
- Devise and implement quantum-coherent strategies for *computation* and *communication*
Magneto-Electronics

1st generation spintronic devices based on ferromagnetic metals – already in commercial use

GMR $\rightarrow$ read-out heads in hard drives

Magnetic tunneling junction (MTJ) or “spin valve” $\rightarrow$
Nonvolatile MRAM:
“Microchips that never forget”

Compatibility with Si and GaAs $\rightarrow$ next phase:
semiconductor spintronics

S. Parkin (1990)
Recent Discoveries in Semiconductors

- A room temperature, optically induced, very long lived quantum coherent spin state in semiconductors that responds at Terahertz with no dissipation and can be transported by small electric fields (UCSB).

- Ferromagnetism in semiconducting GaMnAs at 120K (Japan, Europe, U.S.A.).

DARPA ‘Spins in Semiconductors’ Program (2000 – present)
Spin-Enhanced and Spin-Enabled Electronics

• **Quantum Spin Electronics**
  – Tunneling/transport of quantum confined spin states
  – Spin dependent resonant tunneling devices and spin filtering
  – Spin FETs (“spin gating”)
  – Spin LEDs, electroluminescent devices, and spin lasers

• **Coherent Spin Electronics**
  – Optically generated coherent spin states and coherent control of propagating spin information - optical encoders and decoders

• **Quantum Information Processing**
  – Qubits using coherent spin states \( a|0> + b|1> \), \( a^2 + b^2 = 1 \)
  – Spin based quantum computing, teleportation, code breaking and cryptography
Quantum Information Processing

- Coherent superposition: $\left| \psi \right\rangle = a\left| 0 \right\rangle + b\left| 1 \right\rangle$

  $\rightarrow$ Inherent parallelism $\rightarrow$ can solve problems that are computationally too intensive for classical computers

- 2 examples of ‘quantum algorithms’:
  
  Shor’s factorization (1994)
  Grover’s search (1997)

- Quantum entanglement, EPR pair, quantum teleportation

- Physical Implementations:
  
  Trapped ions (1995)
  Cavity QED (1995)
  Bulk NMR (1997), ... 

\[\text{Proof-of-principle demonstrations, but not scalable}\]
Toward Solid-State Realization of QIP

The Race is on!

- Intensive search for realistic approaches to building a quantum computer
- Solid-state systems offer a much greater degree of control over design and fabrication, necessary for constructing large-scale devices

Semiconductors vs. Superconductors
  - Spin Qubits vs. Charge Qubits
  - Cooper Pairs vs. Flux Qubits
  - Electron Spin vs. Nuclear Spins

Electrical Manipulation vs. Optical Manipulation
Decoherence Problem

- Coherent states are very easily damaged by uncontrolled interactions with the environment – *decoherence*
- Unavoidable decoherence will cause the quantum information to decay → main obstacle
- Decoherence causes a collapse of the superposition state into a single eigenstate → loss of parallelism

$T$ : decoherence time
$t$ : operation time
$R = T/t$ : figure of merit

How can we increase $T$ and/or decrease $t$?
Our Goal

To develop novel **ultrafast optical methods** in semiconductors that may find application in **spintronics** or **quantum information science** through **coherent** light-matter interactions involving **ferromagnetism, band structures, lattice vibrations**, and **excitons**
Ultrafast Photoinduced Softening (UPS) in InMnAs

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Ultrafast Optics in Ferromagnetic Metals

E. Beaurepaire et al., PRL 76, 4250 (1996); PRB 58, 12134 (1998).

- **Ultrafast demagnetization** (~ hundred fs) and slow recovery
- Possible application to ultrafast magneto-optical recording
Low-temperature MBE grown $\text{III}_{1-x}\text{Mn}_x\text{V}$:
- InMnAs: $T_c < 60$ K
- GaMnAs: $T_c < 170$ K

Mn ions ($\text{Mn}^{2+}$) = acceptors & local magnetic moments ($3d^5$, $S = 5/2$)

Mn-Mn exchange: hole mediated

Carrier density tuning

External control of ferromagnetism
Advantages of Ferromagnetic Semiconductors over Ferromagnetic Metals

- Ultrafast pump $\rightarrow$ primarily increases carrier density (rather than carrier temperature)
- Created carriers interact with Mn ions $\rightarrow$ enhance Mn-Mn exchange interaction
- Circular-polarized pump $\rightarrow$ spin polarized carriers
- Low-$T$ MBE growth $\rightarrow$ ultrashort lifetimes
Ultrafast Carrier Dynamics in InMnAs

(1) carrier trapping
(~ 2 ps)

(2) Carrier recombination of trapped carriers

Pump = 1260 nm
Probe = 775 nm
In$_{0.91}$Mn$_{0.09}$As(25nm)/GaSb(820nm) on GaAs(100)

$T_c = 55$ K
Two-Color Pump & Probe

- Selective pumping of InMnAs by fs MIR pulses
- Photogenerated, transient spin-polarized carriers
- Probe time-dependent ferromagnetism
Ultrafast Photoinduced MOKE

J. Wang et al., J. Supercond. 16, 373 (2003); Physica E, in press; cond-mat/0305017

$T = 16$ K
$T_c = 55$ K
$H = 0$ Oe
Pump: 2 μm
Probe: 775 nm
Ultrafast Photoinduced Softening

J. Wang et al., J. Supercond. 16, 373 (2003); Physica E, in press; cond-mat/0305017

- Loop shrinks horizontally and then comes back!
- First demonstration of ultrafast optical manipulation of coercivity
Nonthermal Magnetooptical Recording

Spin flipping $\rightarrow$ ultrafast information recording

$t = 0$

$H_c^0$

$H_{c_{mod}} < H_{ex} < H_c^0$

$t > 0$

$\sim 100$ fs
Dynamic Franz-Keldysh Effect (DFKE) in GaAs: Optical absorption in AC-driven solids

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1. Predictions
2. Observations
3. Interpretation
4. Significance

Ultrafast bandgap engineering
Wiggling Electron in a Laser Field

\[ E(t) = E_0 \cos \omega t \]
\[ v(t) = \frac{eE_0}{m} \sin \omega t \]
- wiggly motion

\[ \langle K.E. \rangle = \frac{1}{T} \int_0^T \frac{1}{2} mv^2 \, dt = \frac{e^2 E_0^2}{4m \omega^2} = U_p : \text{ponderomotive potential} \]

\[ \hbar \ll U_p : \text{DC-FKE} \]
\[ \hbar \gg U_p : \text{Multiphoton transition} \]
Bloch Electron in a Laser Field

Time-Periodic Potential vs. Space-Periodic Potential

Relevant length scale: \( a = \frac{eE_0}{m\omega^2} \)

\[ U_p \begin{array}{c} \hbar \end{array} \iff \begin{array}{c} B \end{array} \begin{array}{c} \hbar \end{array} \iff \begin{array}{c} a \end{array} \begin{array}{c} a_0 \end{array} \]

\( (\hbar_B = ea_0E_0 / \hbar) \)
How to realize $a \sim a_0$

- Intense MIR fs pulses
- Easier at longer wavelengths
- Required Intensity (W/cm$^2$) vs. Wavelength (µm)
  - Ti:Sapphire
  - Nd:YAG
  - FEL
  - OPA

$E_{\text{int}} = \mu E_{\text{in}}$

$1 \leq \mu \leq 10$
Dynamic Franz-Keldysh Effect


Transition rate (a.u.)

-1.0  -0.5  0.0  0.5  1.0

$\hbar - E_g$ (in units of $\hbar$

with pump
without pump

Exponential tail

Blue shift of band edge → transparency

$\alpha \square \alpha_0$
Photoinduced Transparency

GaAs film

Pump energy = 138 meV

~40% photoinduced transparency

Absorption below band edge

Band edge of GaAs

Room temp.

T_pump on / T_pump off

Phonon energy (eV)
DFKE Simulation for a GaAs Film

- Undoped GaAs film (2.7 μm thick)
- Multiple-reflection included
- $\lambda_{\text{pump}} = 9 \mu\text{m}$ (138 meV)
- $I_{\text{pump}} = 10^{10} \text{ W/cm}^2$

Induced transparency
Intense MIR laser fields can coherently modify electronic states in solids through non-resonant pumping.

- No sample damage, no real carriers

- Ultrafast transmission quenching below band edge observed

- First observation of induced transparency above the band edge

- Main features of observations qualitatively agree with theory
Summary

Ultrafast Optical Control in Semiconductors

Accomplished:

• Photogenerated transient carriers → modify magnetic properties in InMnAs → first demonstration of ultrafast softening: $H_c$ (coercivity) decreases (‘hard’ → ‘soft’)

• Intense and coherent midinfrared radiation modified band structure through DFKE → first observation of ultrafast photoinduced transparency

In Progress:

• Demonstration of ultrafast photoinduced magnetization reversal
• Transient modifications of $T_c$ and photoinduced transient para- to ferromagnetic transition
Realization of Spin-Based Devices

Technical issues

• How strongly can one create carriers of a given spin?

• How long can one sustain the spin polarization?

• How can one modulate or control the spin?

• How sensitively can one detect the spin?
Decoherence Problem

- Coherent states are very easily damaged by uncontrolled interactions with the environment – *decoherence*
- Unavoidable decoherence will cause the quantum information to decay, thus inducing errors in the computation
- Decoherence occurs rapidly in complex big systems, which is why we never observe macroscopic superpositions

\[
T : \text{coherence time} \\
t : \text{operation time} \\
R = T/t : \text{figure of merit}
\]

Factoring a 4-bit number using Shor’s algorithm
Requires \(\sim 2 \times 10^4\) gate operations on 20 qubits \(\rightarrow\)
\(R\) has to be \(> 4 \times 10^5\)
Ultrafast Optics in Ferromagnetic *Metals*

**Ni and Co:**

**CoPt₃:**

*Ultrafast pump ➔ Electronic heating ➔ Microscopic understanding elusive*
CW Optical Control of Ferromagnetism


- Light-induced ferromagnetism
- Light-induced coercivity decrease
- Persistent photoeffect
Persistent Photoeffect

- Electron-hole separation
- Hole density increases persistently
- Slow
- Not reversible
Regen + OPA + DFG
= tunable source of intense MIR pulses

775 nm
140 fs, 1 mJ

Ti:S Regenerative Amplifier

signal + idler up to 100 µJ

1.1 µm to 1.6 µm
idler
1.6 µm to 3 µm

Optical Parametric Amplifier

signal

Difference Frequency Generator

PRB 65, 121307(R) (2002)
PRL 86, 3292 (2001)
PRL 85, 3293 (2000)
Experimental Setup

- **OPA**
- **CPA**
- **Balanced detector**
- **Wallston prism**
- **Transient MOKE**
- **Transient Reflection**
- **PUMP MIR**
- **MIR**

**Parameters:**
- **2 μm**
- **775 nm, 150 fs, 1 mJ, 50 ~ 1 K Hz**
- **10⁻⁵**

Graph showing:
- **MOKE Signal vs. Time Delay**
- **R/R vs. Time Delay**
InMnAs-Based Heterostructures

- **Type-II** broken gap heterostructures with AlGaSb
- **First ferromagnetic** $p$-type films, $T_c = 7$ K (1991), $T_c = 35$ K in $p$-InMnAs/GaSb (1993)
- **Light-induced** ferromagnetism (1997)
- **Electrical tuning** of ferromagnetism (2000)
Carrier Dynamics in InMnAs

(1) carrier trapping
(~ 2 ps)
(2) recombination of trapped carriers

Pump 2 [m, 0.5 mW
Probe 775 nm
Pump-Polarization Dependence

MOKE Signal (V)

Time delay (ps)

Magnetic Field (T)

-8x10^{-5}

-4

-2

0

2

4

6

8

-8x10^{-5}

-0.2

-0.1

0

0.1

0.2

20K

\( t = 0 \)

\( t = -4 \text{ ps} \)

\( \downarrow^+ \) pumping

\( \downarrow^- \) pumping
MOKE Dynamics above $T_c$

→ Not related to ferromagnetism
→ This is due to **carrier spin**
What determines coercivity?
-- Anisotropy & Exchange

- Anisotropy \((K)\) does NOT change with carrier density
- Exchange increases

Decreased domain wall energy → Smaller coercivity
Ultrafast Photoinduced Softening

Diagram 1: Graphs showing the change in \( \theta_k \) (arb.) with respect to \( B \) (mT) and time delay (ps). 

- (b) Shows a plot with varying \( \theta_k \) and \( B \) over time. 
- (c) Displays a similar plot with a different \( \theta_k \) range. 
- (d) Illustrates a plot with a distinct \( \theta_k \) range. 
- (e) Presents a corresponding \( \theta_k \) and \( B \) plot with a specific time delay of 2 ps.
Limitations

- Curie temperature ($T_c$) of InMnAs below room temperature → explore new materials (e.g., GaMnN)
- Small band gap of InMnAs requires powerful mid-infrared (MIR) laser pulses → requires development of compact MIR source or large band gap materials (e.g., GaMnN)
- Kerr rotation angle of InMnAs small → new materials or sophisticated optical arrangements necessary
Franz-Keldysh Effect

E-field-induced changes in optical absorption near the bandedge

Additional term in the Hamiltonian

\[ \mathcal{H}' = [e \mathbf{E} \cdot \mathbf{r}] \]

dc field

Exponential for positive arguments

Oscillations for negative arguments

Exponential tail below bandgap

Oscillations above bandgap

Wavefunction

Absorption

Exponential for positive arguments

Oscillations for negative arguments

Exponential tail below bandgap

Oscillations above bandgap
Unusual Power Dependence

Below band gap absorption in bulk GaAs at 300 K

Decreasing intensity  Increasing effect!!

Transmission vs. Photon Energy (eV)
Extent of Induced Absorption

Polycrystalline ZnSe, 3.5 μm driving field, ~ 1

Induced absorption extends almost 1 eV below $E_g$!
Other Strong-Field-Induced Effects in Semiconductors

DC Franz-Keldysh effect

AC Stark effect

shift ~ only a few meV at 100 kV/cm!

DFKE is a
dramatic effect
DFKE Simulation for GaAs


GaAs

\( n_{\text{pump}} = 9 \times 10^6 \text{ m (}h\text{)} = 138 \text{ meV} \)

\( I_{\text{pump}} = 10^{10} \text{ W/cm}^2 (U_p \sim h?) \)

Induced absorption

Blue shift of band edge → Induced transparency
Pump Wavelength Dependence

GaAs film

\[
\text{Room temp.}
\]

Band edge of GaAs
Experiments