RICE UNIVERSITY

ECE Affiliates Meeting October 8, 2003

Optical Control in Semiconductors for Spintronics and Quantum Information Processing

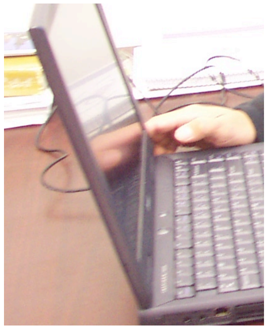
Jun Kono

Department of Electrical & Computer Engineering, Rice University

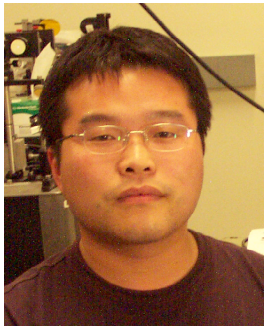
Supported by **NSF DMR-0325474 (ITR)**, **NSF DMR-0134058 (CAREER)**, **NSF INT-0221704**, and **DARPA MDA972-00-1-0034 (SpinS)**

Our Spin/Q.I.P. Team

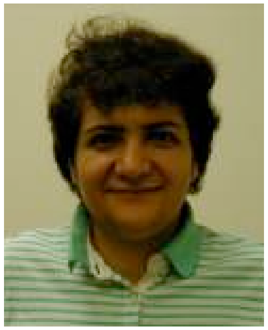
RICE UNIVERSITY


Jigang Wang


Ajit Srivastava


Xiangfeng Wang


Rahul Srivastava


Giti Khodaparast

Univ. of Florida


Chris Stanton


Dave Reitze


Young-Dahl Jho

NHMFL

NSF

DARPA

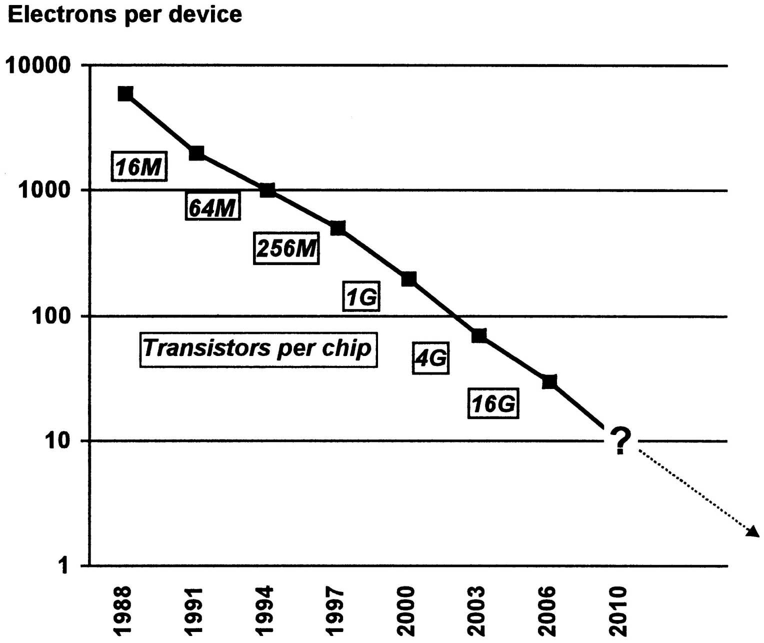
UCSD


Lu Sham

Tokyo Inst.
of Technology


Hiro Munekata

Need for *Quantum* Technologies



> “***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

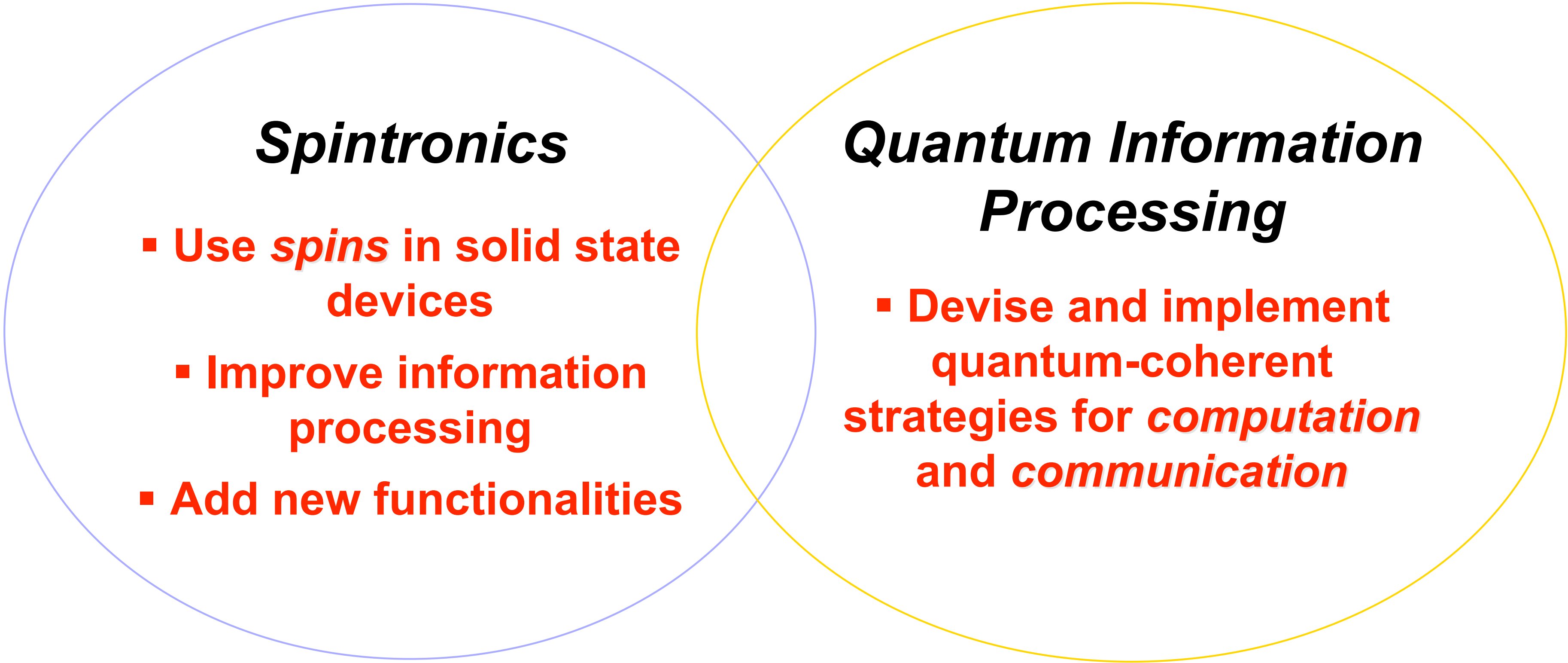
- Miniaturization – **approaching a physical limit**
- Quantum effects – statistical, fuzzy, strange – unavoidable
- Novel **quantum technologies** being sought → better performance and new functionality and multi-functionality
- **Spin-based** electronics, quantum electronics based on quantum **coherence**,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

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**

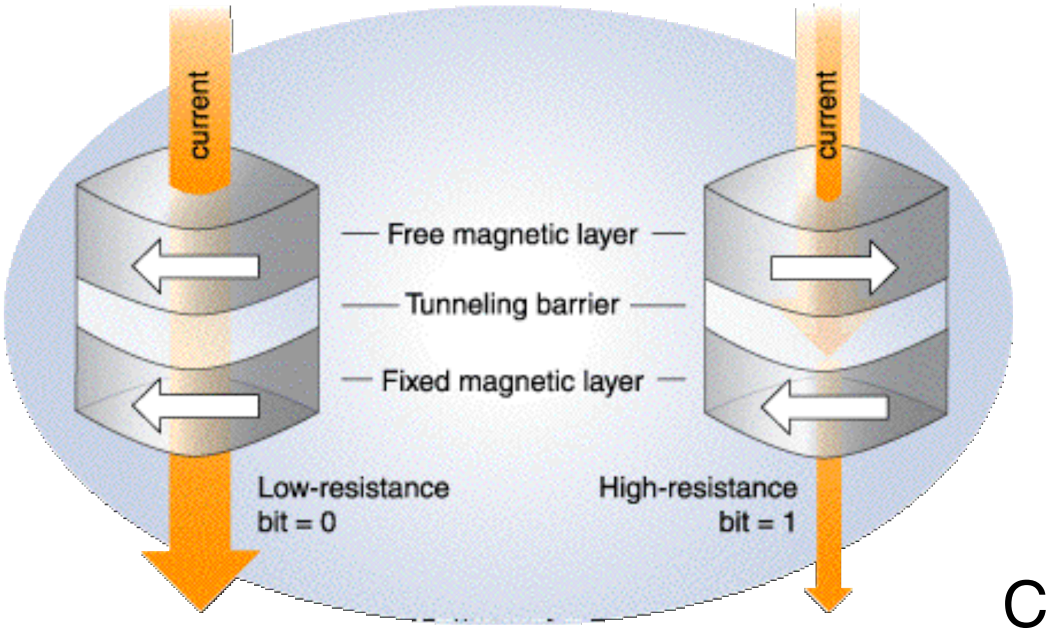
Quantum Information Processing

- **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 → read-out heads in hard drives



S. Parkin (1990)

Magnetic tunneling junction (**MTJ**) or “spin valve” → Nonvolatile **MRAM**: “***Microchips that never forget***”

Compatibility with Si and GaAs → next phase: ***semiconductor spintronics***

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: $|\Box\rangle = a|0\rangle + b|1\rangle$

  → Inherent parallelism → 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

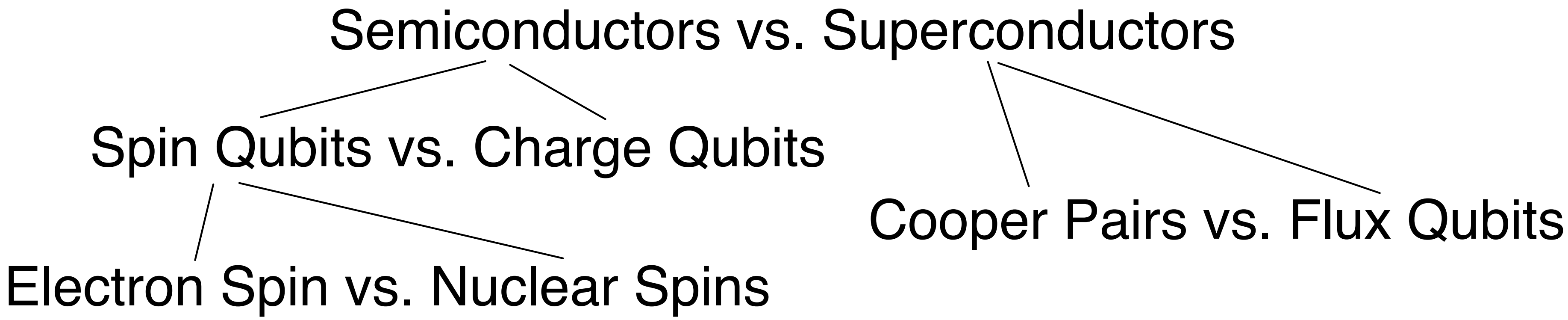
- Physical Implementations:
  - Trapped ions (1995)
  - Cavity QED (1995)
  - Bulk NMR (1997), …

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

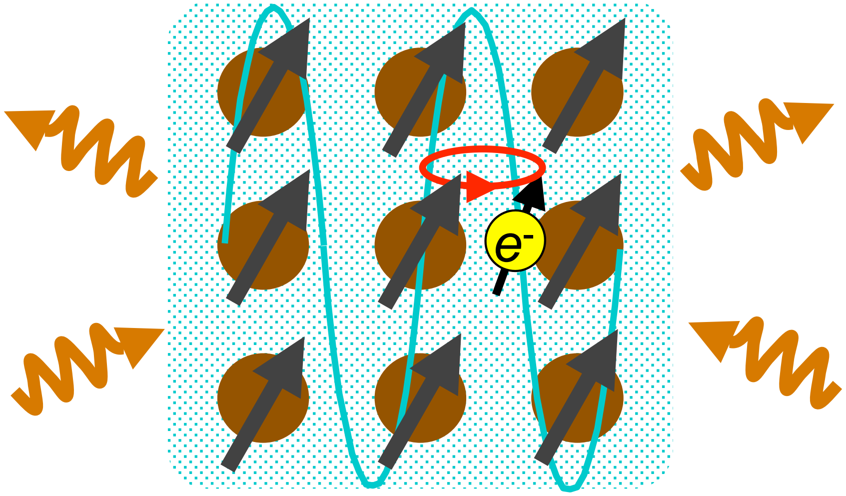
Decoherence Problem

- 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

J. Wang, G. A. Khodaparast & J. Kono

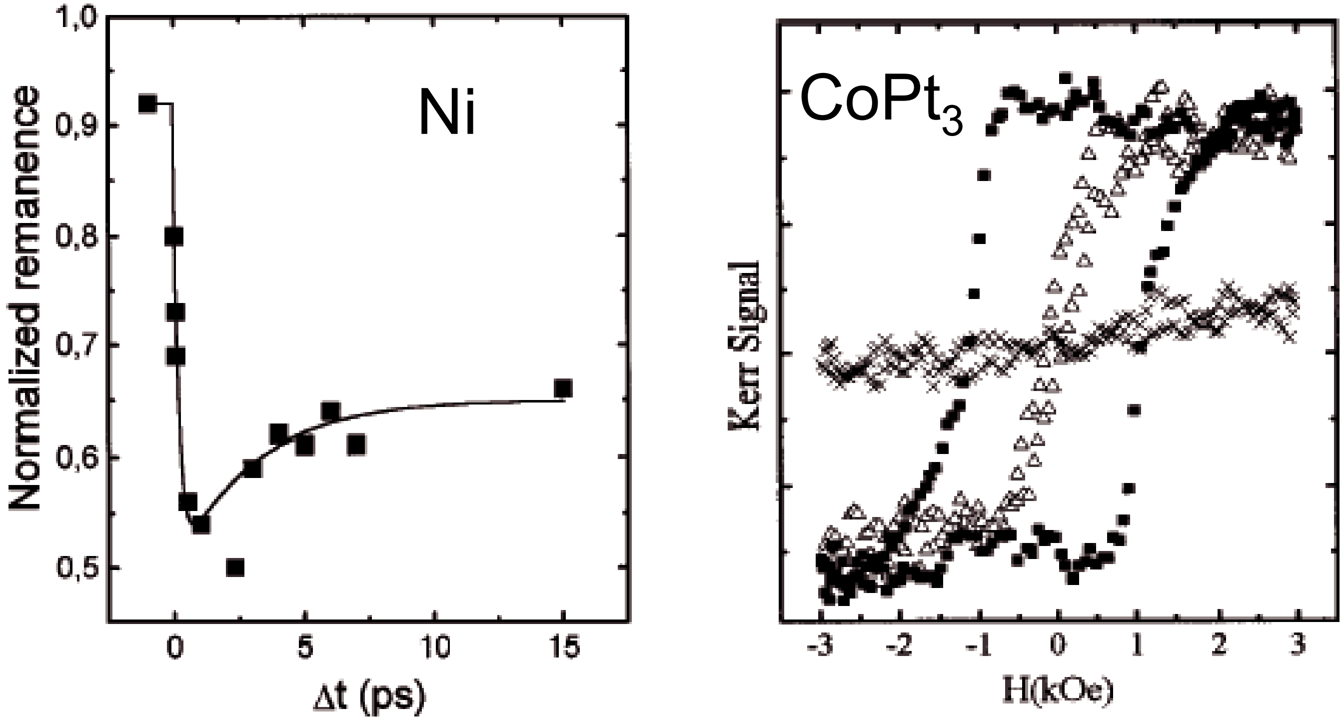
Rice University

T. Slupinski, A. Oiwa & H. Munekata

Tokyo Institute of Technology

Ultrafast Optics in Ferromagnetic *Metals*

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



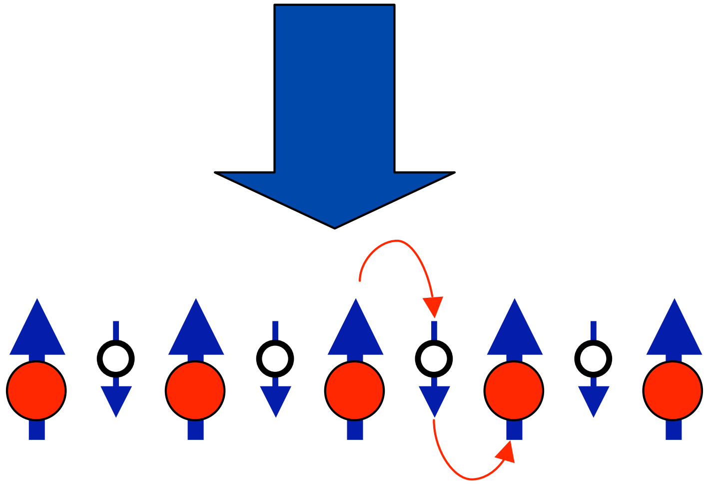
- **Ultrafast demagnetization** (~ hundred fs) and slow recovery
- Possible application to ultrafast **magneto-optical recording**

III-V Ferromagnetic Semiconductors

Low-temperature MBE grown $\mathrm{III}_{1-x}\mathrm{Mn}_x\mathrm{V}$:

- InMnAs: $T_c < 60$ K
- GaMnAs: $T_c < 170$ K

Mn-Mn exchange: hole mediated



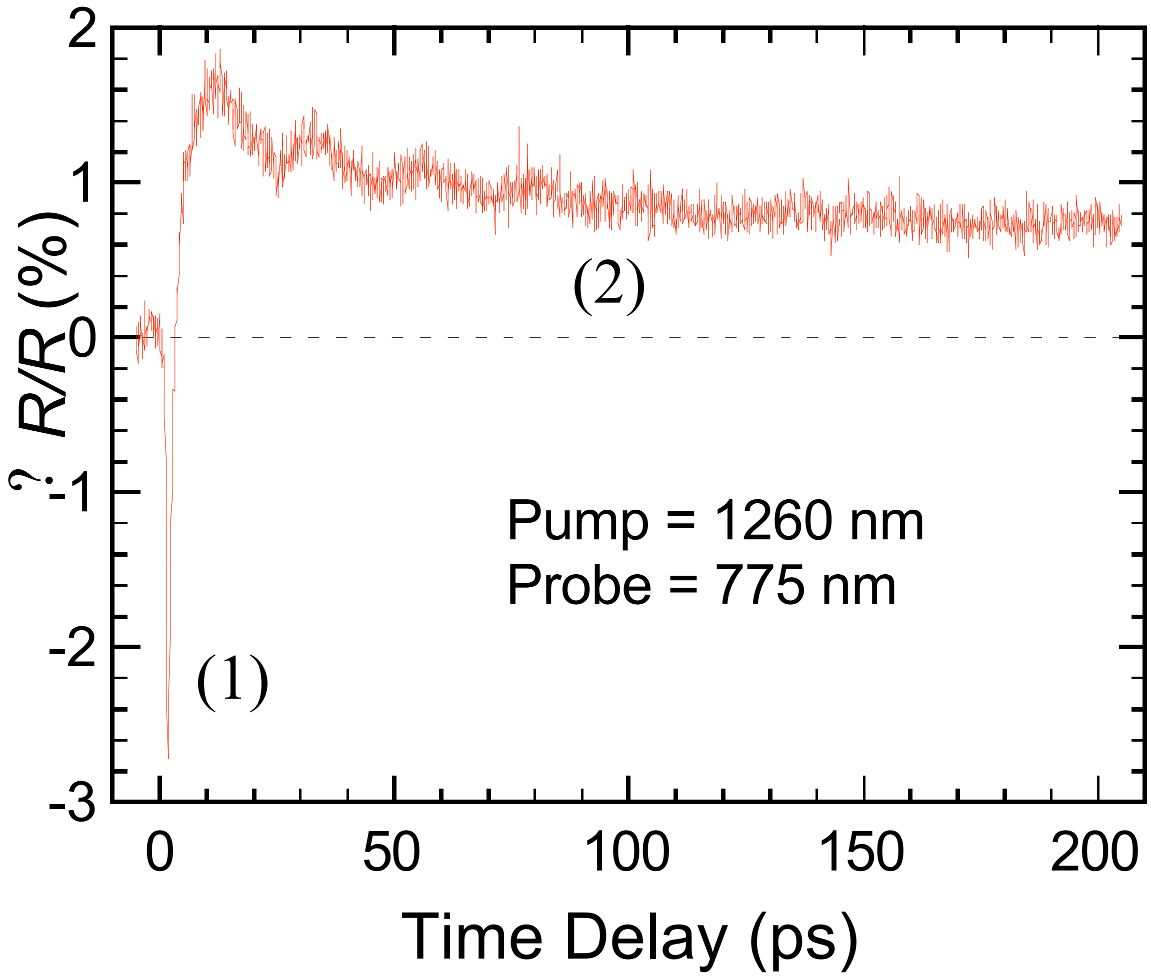
Mn ions (Mn^{2+}) = **acceptors** & **local magnetic moments** ($3d^5$, $S = 5/2$)

Carrier density tuning → **External control of ferromagnetism**

Advantages of **Ferromagnetic Semiconductors** over **Ferromagnetic Metals**

- Ultrafast pump → primarily ***increases carrier density*** (rather than *carrier temperature*)
- Created carriers interact with Mn ions → ***enhance Mn-Mn exchange interaction***
- Circular-polarized pump → ***spin polarized carriers***
- Low-T MBE growth → ***ultrashort lifetimes***

Ultrafast Carrier Dynamics in InMnAs

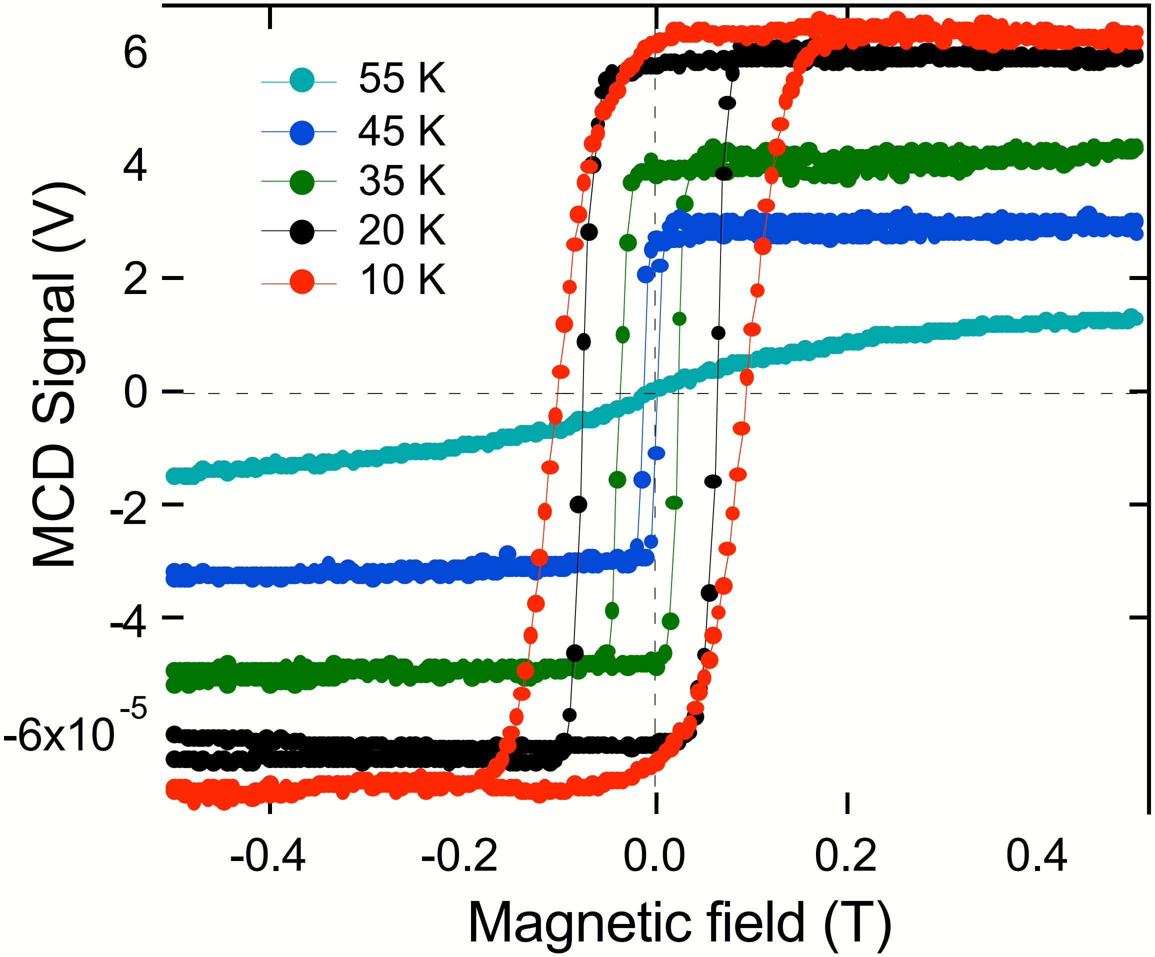


(1) carrier trapping

(~ 2 ps)

(2) Carrier recombination of trapped carriers

Magneto-optical Kerr Effect (MOKE)

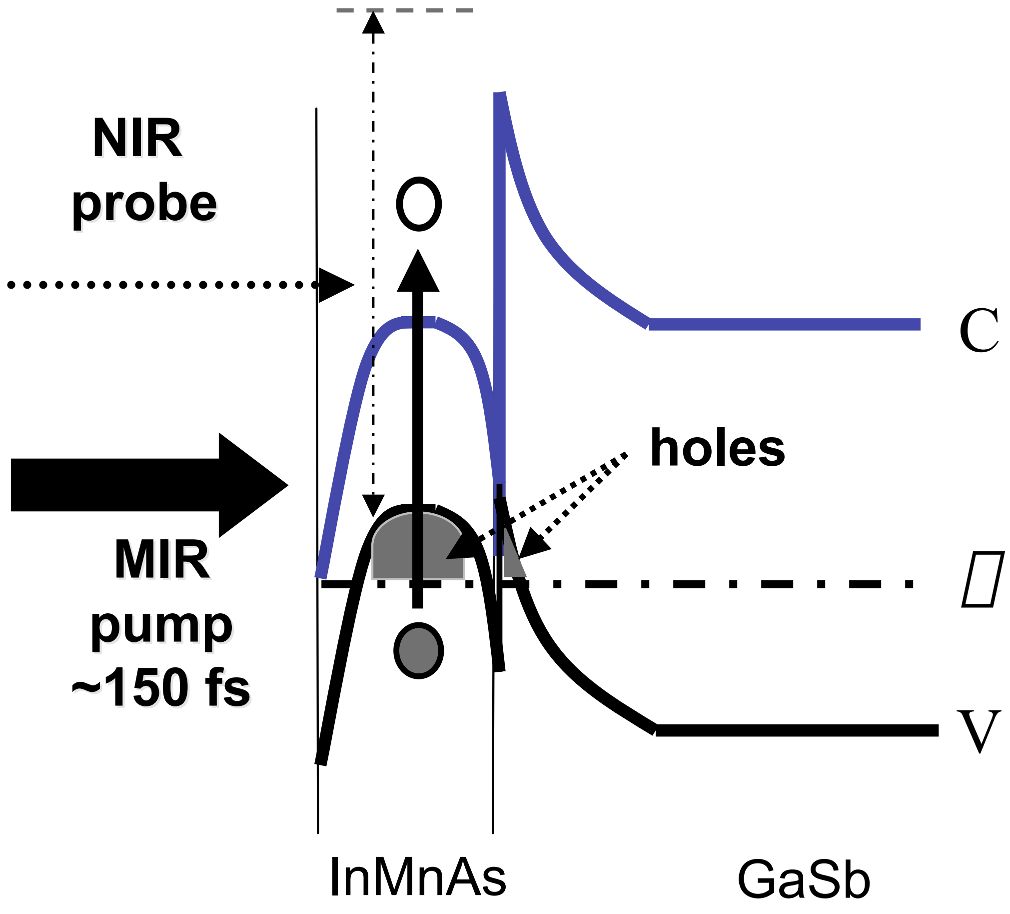


$In_{0.91}Mn_{0.09}As$(25nm)/GaSb(820nm) on GaAs(100)

T_c = 55 K

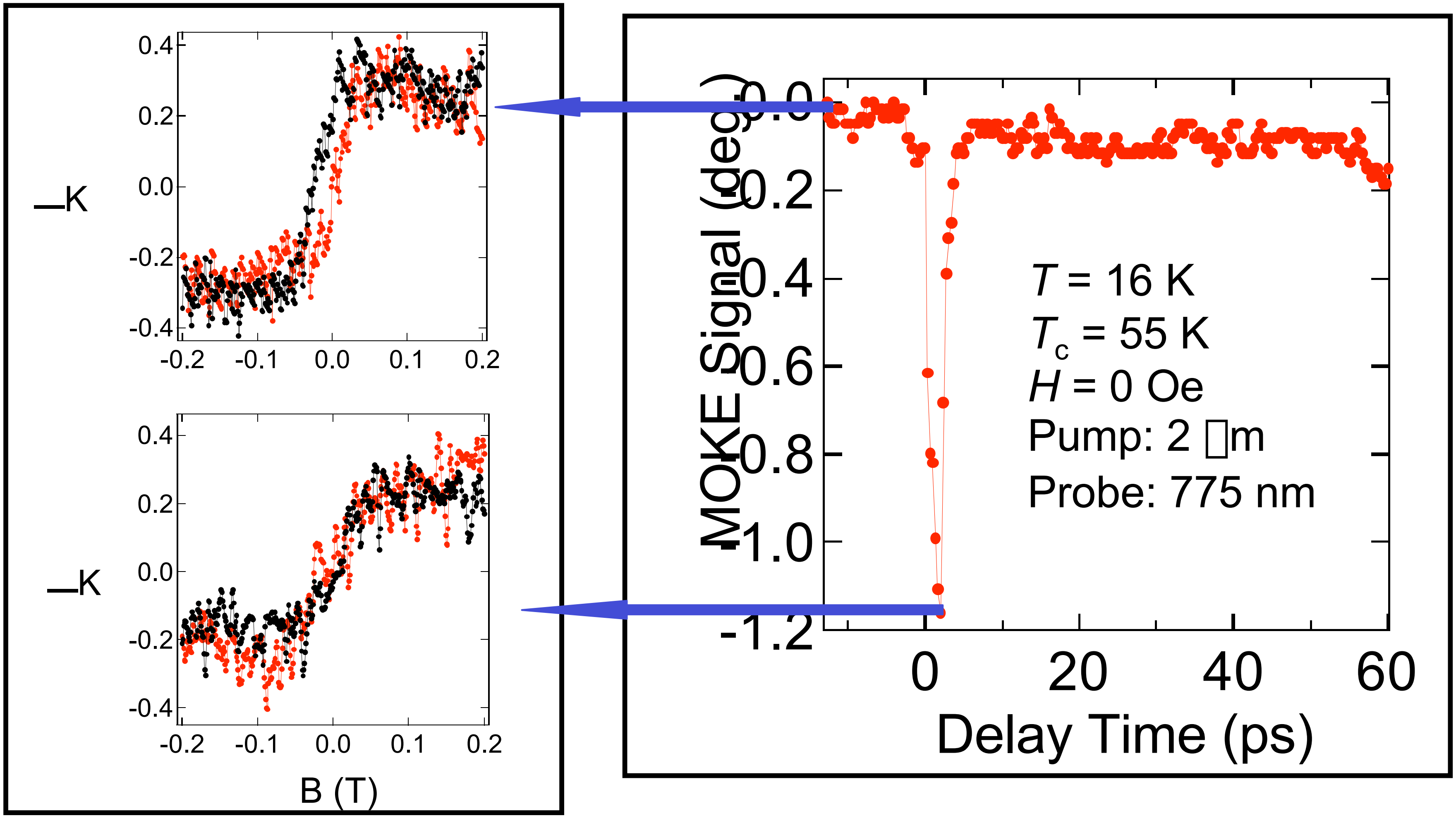
Two-Color Pump & Probe

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



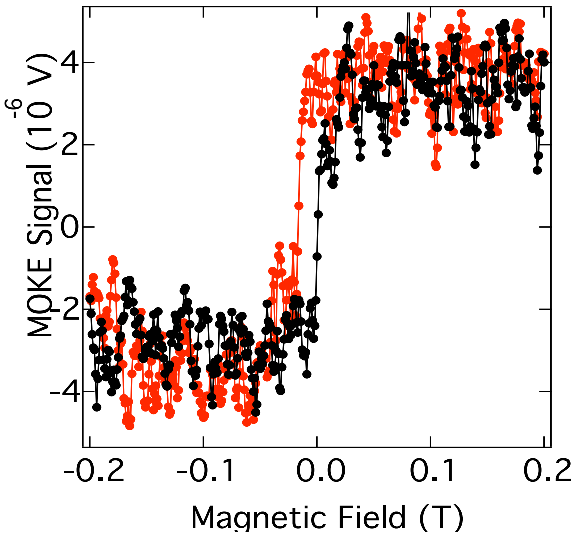
Ultrafast Photoinduced MOKE

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

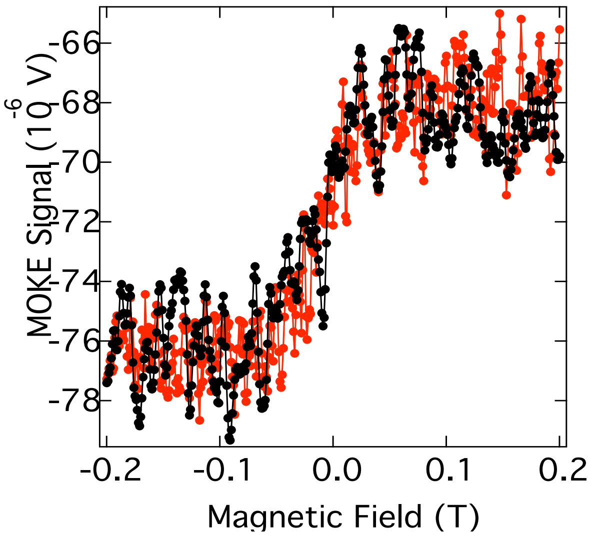


Ultrafast Photoinduced Softening

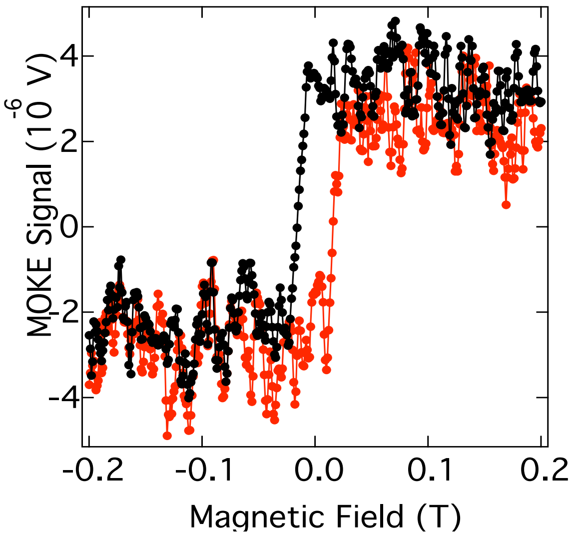
J. Wang *et al*., J. Supercond. **16**, 373 (2003); Physica E, in press; cond-mat/0305017



t ~ −4 ps



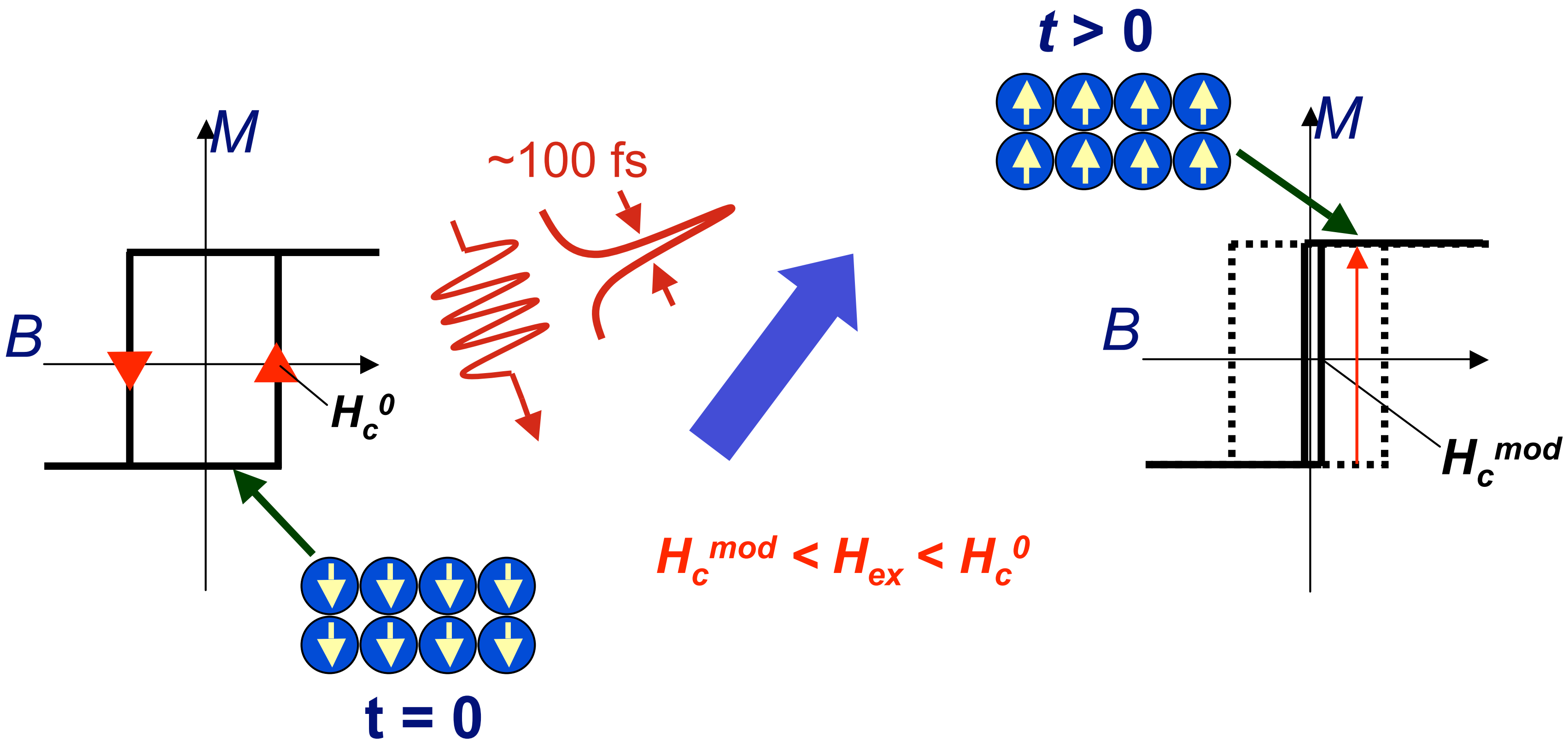
t ~ 0 ps



t ~ 11 ps

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

Nonthermal Magnetooptical Recording



Spin flipping → ultrafast information recording

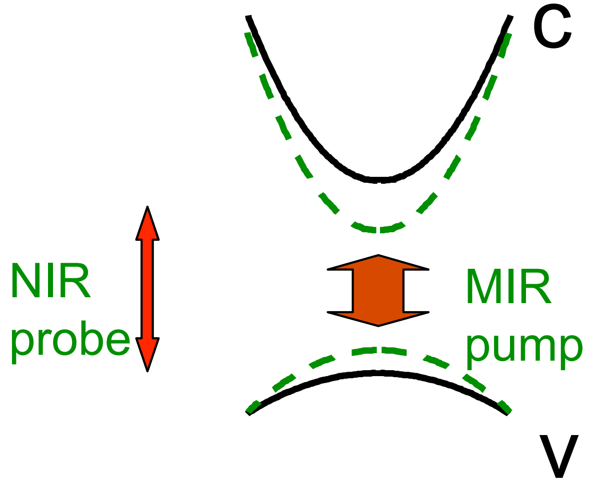
Dynamic Franz-Keldysh Effect (DFKE) in GaAs:

Optical absorption in AC-driven solids

A. Srivastava, R. Srivastava, J. Wang, and J. Kono

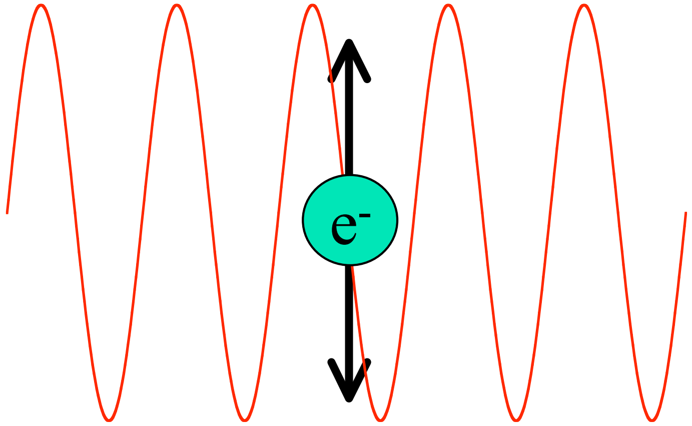
Department of Electrical & Computer Engineering,
Rice University, U.S.A.

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



Ultrafast bandgap engineering

Wiggling Electron in a Laser Field



$$E(t) = E_0 \cos\omega t$$

$$\Rightarrow \quad v(t) = -\frac{eE_0}{m\omega}\sin\omega t$$

– wiggly motion

$$\langle \text{K.E.} \rangle = \frac{1}{T}\int_0^T \left(\frac{1}{2}mv^2\right)dt = \frac{e^2E_0^2}{4m\omega^2} \equiv U_p \text{ : ponderomotive potential}$$

$\hbar\omega << U_p$: DC-FKE

transition

$\hbar\omega >> U_p$: Multiphoton

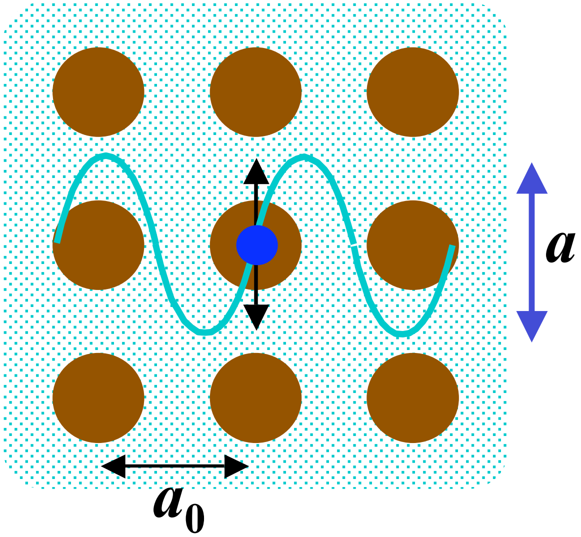
Classical energy U_p

↕

Quantum energy $\hbar\omega$

Bloch Electron in a Laser Field

Time-Periodic Potential
vs.
Space-Periodic Potential

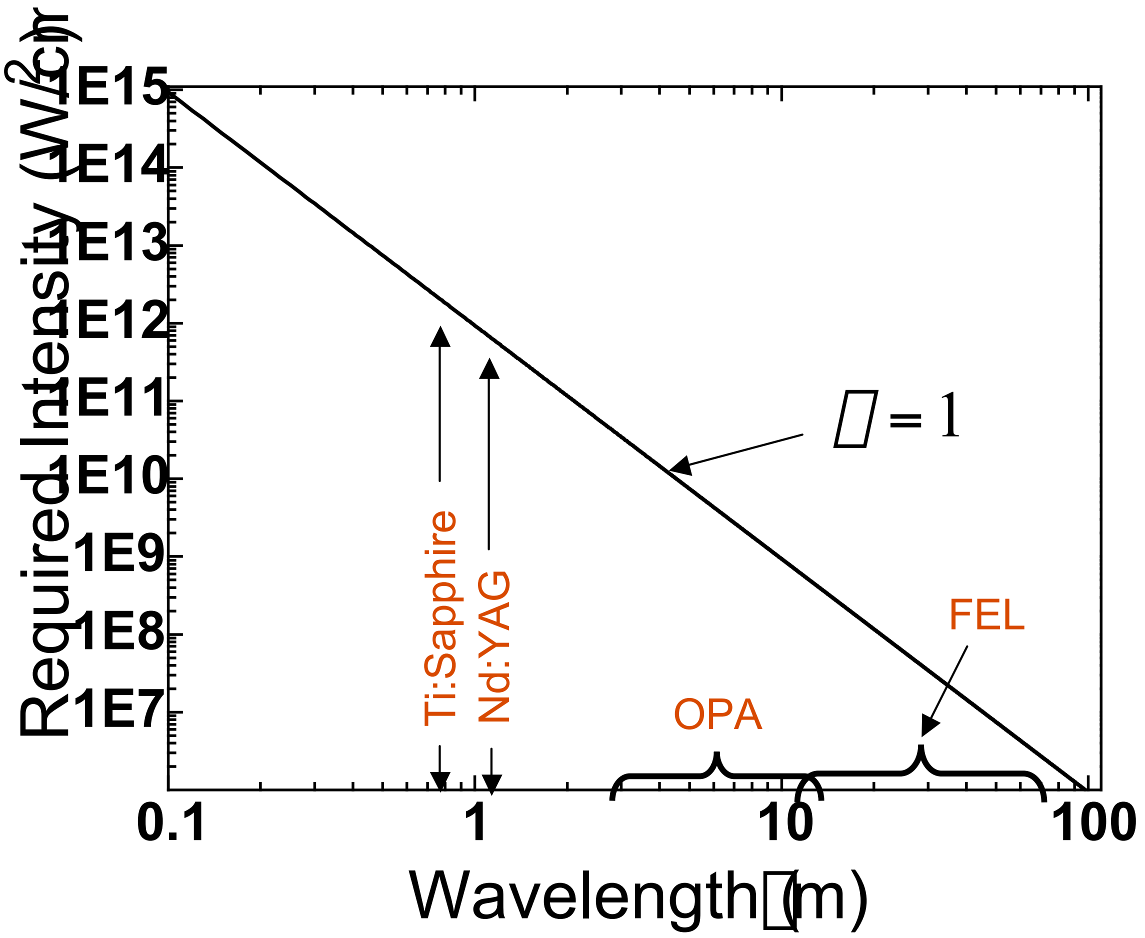


Relevant length scale: $a = \dfrac{eE_0}{m\omega^2}$ ← Oscillation amplitude

$$U_p \sim \hbar\omega \quad \Longleftrightarrow \quad \omega_B \sim \omega \quad \Longleftrightarrow \quad \boxed{a \sim a_0}$$

$$(\omega_B = ea_0E_0/\hbar)$$

How to realize $a \sim a_0$



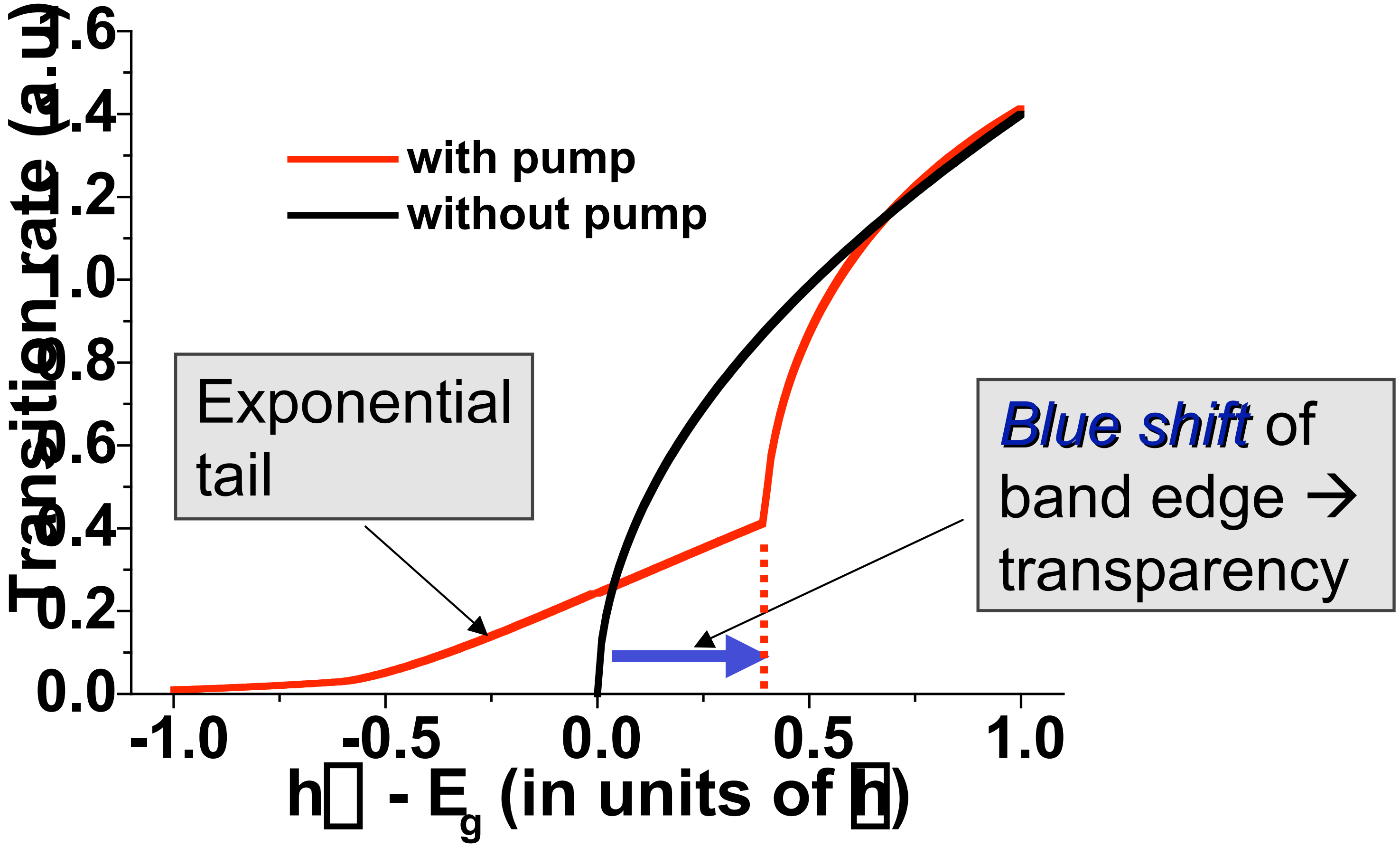
easier at longer wavelengths

Intense MIR fs pulses

Dynamic Franz-Keldysh Effect

Y. Yacoby, PR **169**, 610 (1968).

a □ a_0



Exponential tail

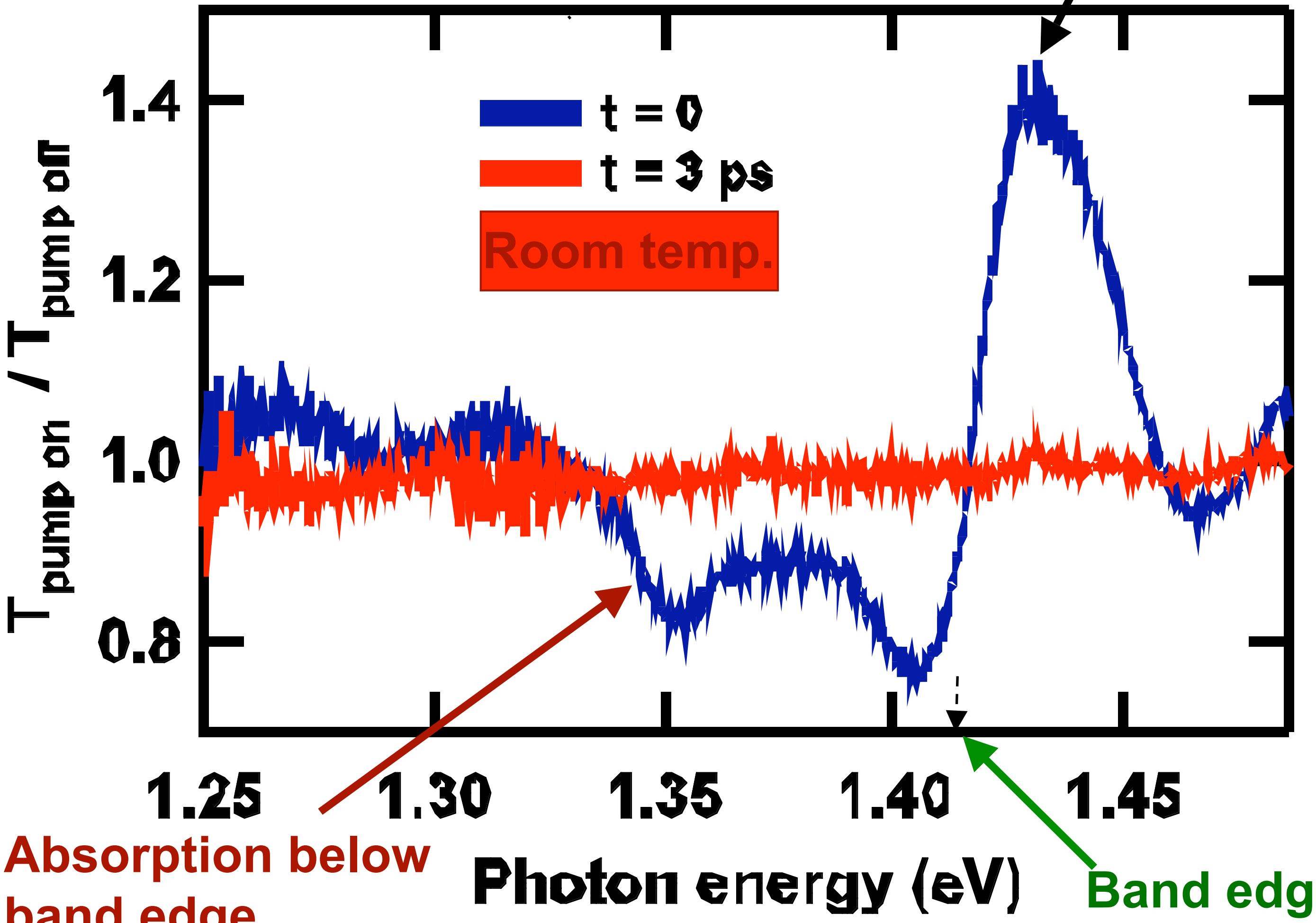
Blue shift of band edge → transparency

Photoinduced Transparency

GaAs film

Pump energy = 138 meV

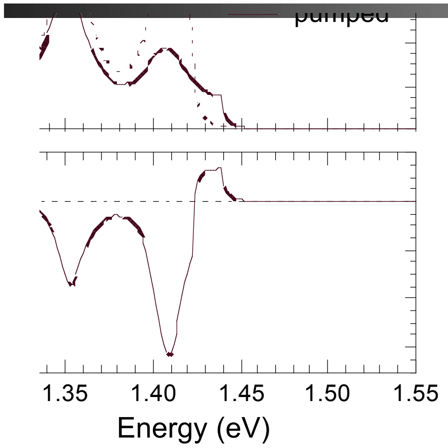
~40% photoinduced transparency



Absorption below band edge

Band edge of GaAs

DFKE Simulation for a GaAs Film



- Undoped GaAs film (2.7 μm thick)
- Multiple-reflection included
- λ_{pump} = 9 μm (138 meV)
- $I_{pump} = 10^{10}$ W/cm^2
- ***Induced transparency***

DFKE: Conclusions

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

Factoring a 4-bit number using Shor's algorithm
Requires ~2×10^4 gate operations on 20 qubits →
R has to be $> 4 \times 10^5$

Ultrafast Optics in Ferromagnetic *Metals*

Ni and Co:

E. Beaurepaire *et al.*, Phys. Rev. Lett. **76**, 4250 (1996).
M. Aeschlimann *et al.*, Phys. Rev. Lett. **79**, 5158 (1997).
A. Scholl *et al.*, Phys. Rev. Lett. **79**, 5146 (1997).
J. Hohlfeld *et al.*, Phys. Rev. Lett. **78**, 4861 (1997).
J. Güdde *et al.*, Phys. Rev. B **59**, R6608 (1999).
B. Koopmans *et al.*, Phys. Rev. Lett. **85**, 844 (2000).

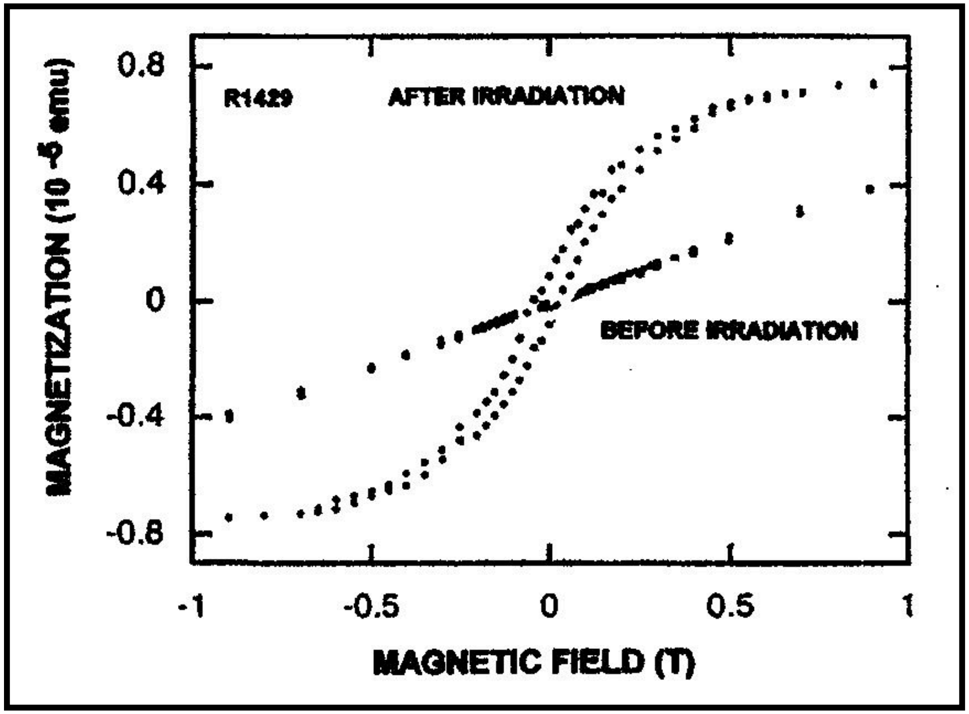
$CoPt_3$:

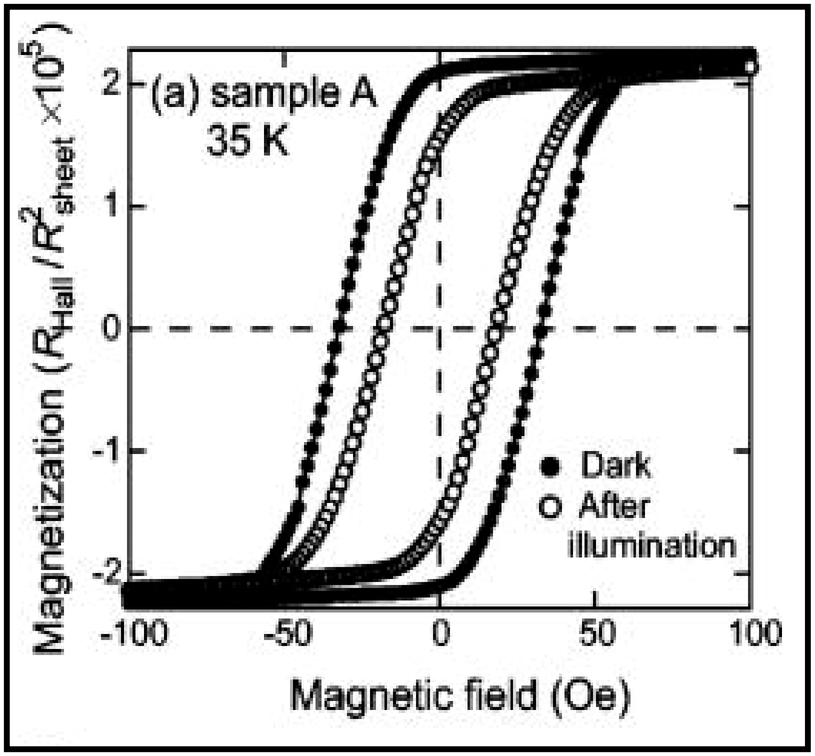
G. Ju *et al.*, Phys. Rev. B **57**, R700 (1998).
E. Beaurepaire *et al.*, Phys. Rev. B **58**, 12134 (1998).
L. Guidoni *et al.,* Phys. Rev. Lett. **89**, 017401 (2002).

Ultrafast pump → Electronic heating
→ Microscopic understanding elusive

CW Optical Control of Ferromagnetism

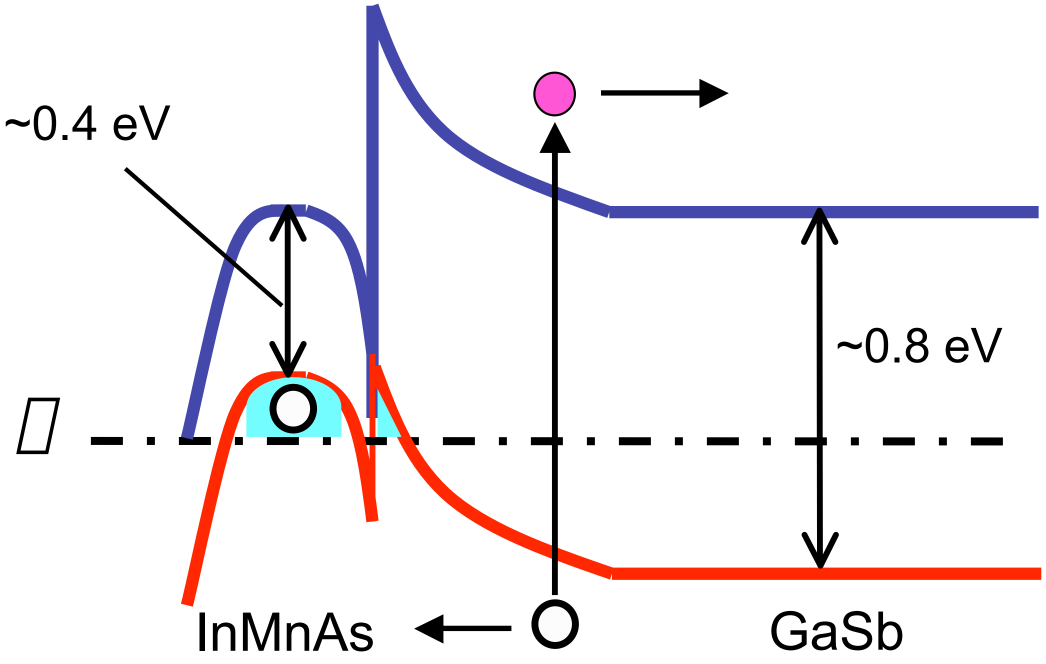
S. Koshihara *et al*., PRL **78**, 4617 (1997); A. Oiwa *et al*., APL **78**, 518 (2001).





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

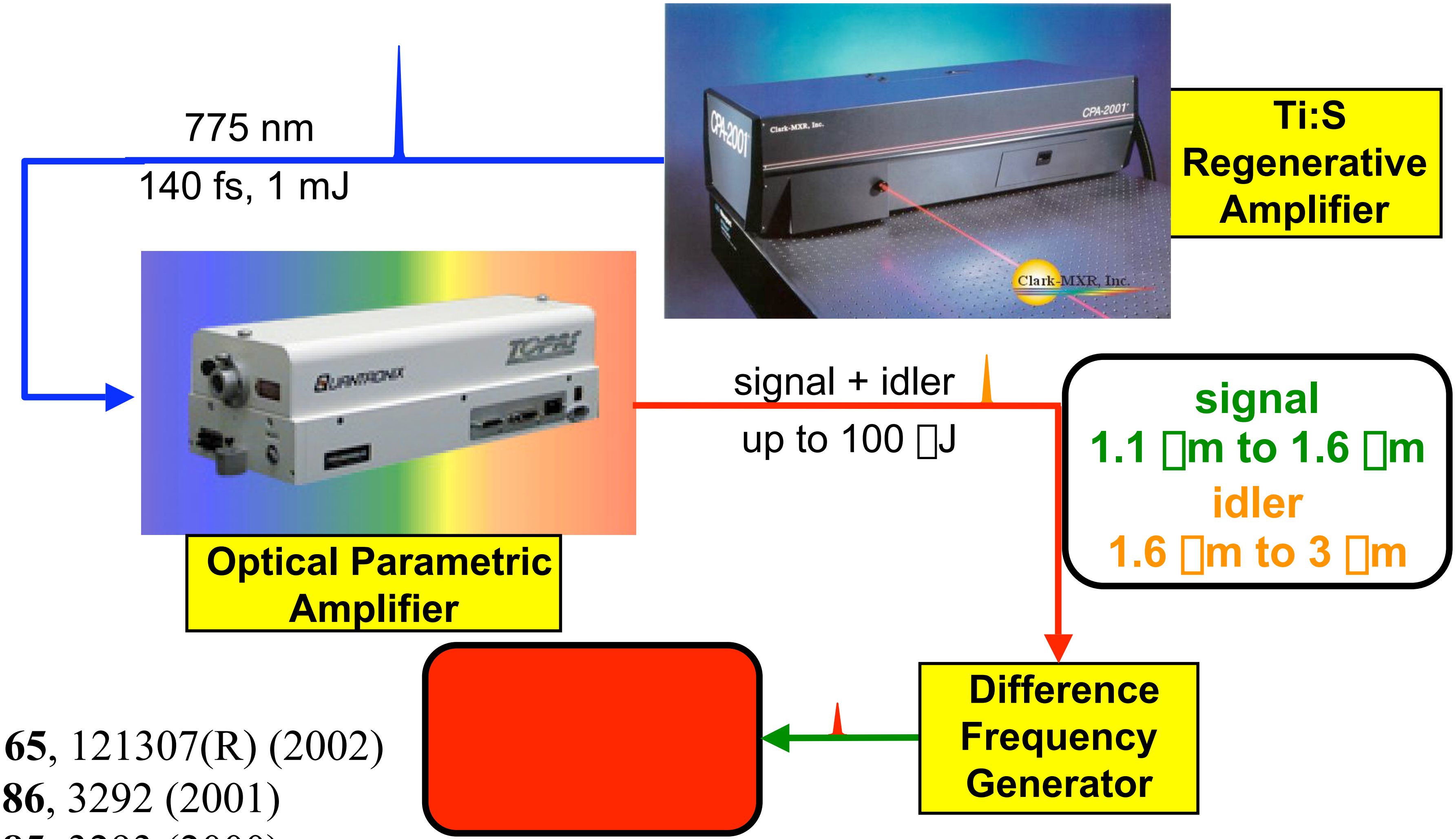
Persistent Photoeffect



- **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

Optical Parametric Amplifier

signal + idler

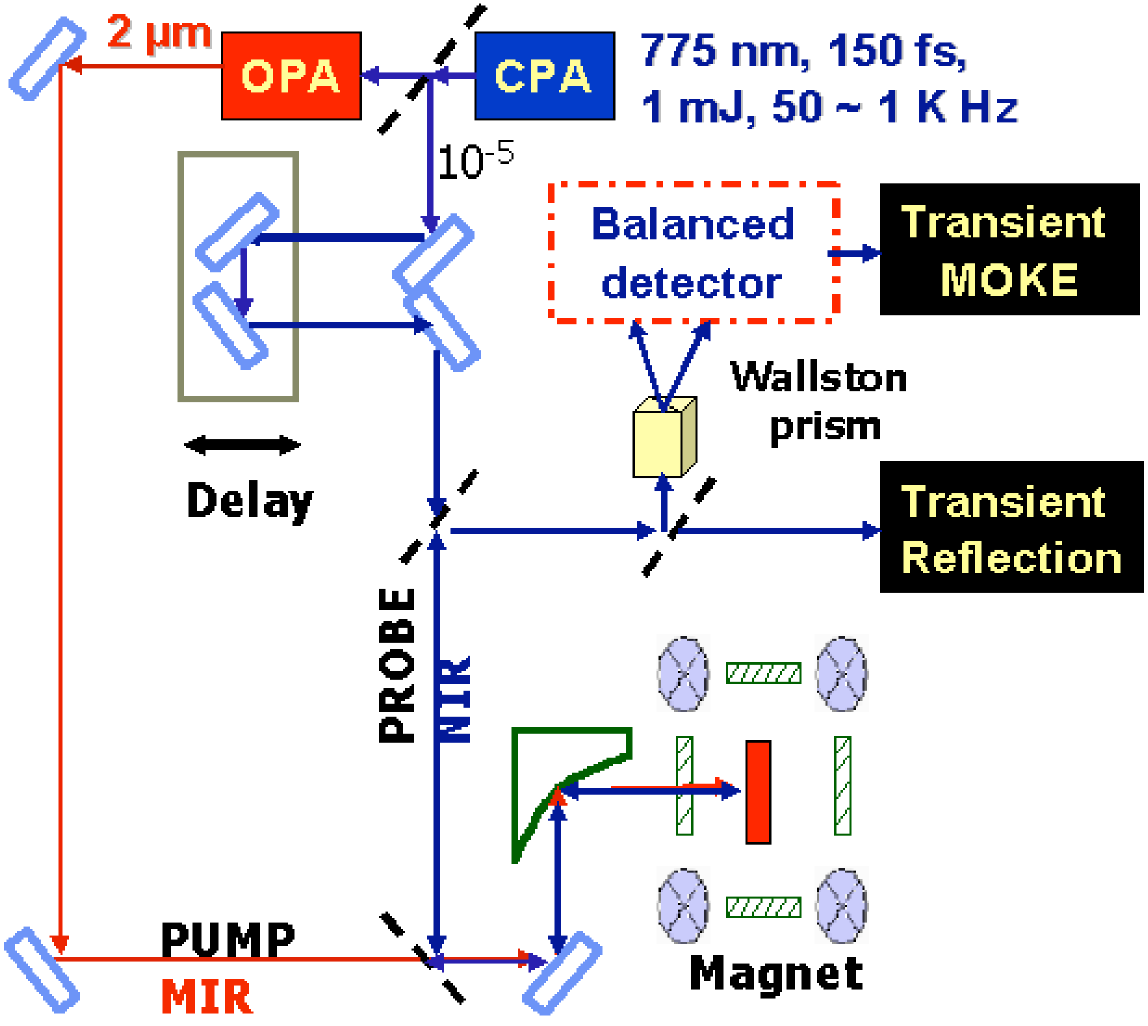
up to 100 μJ

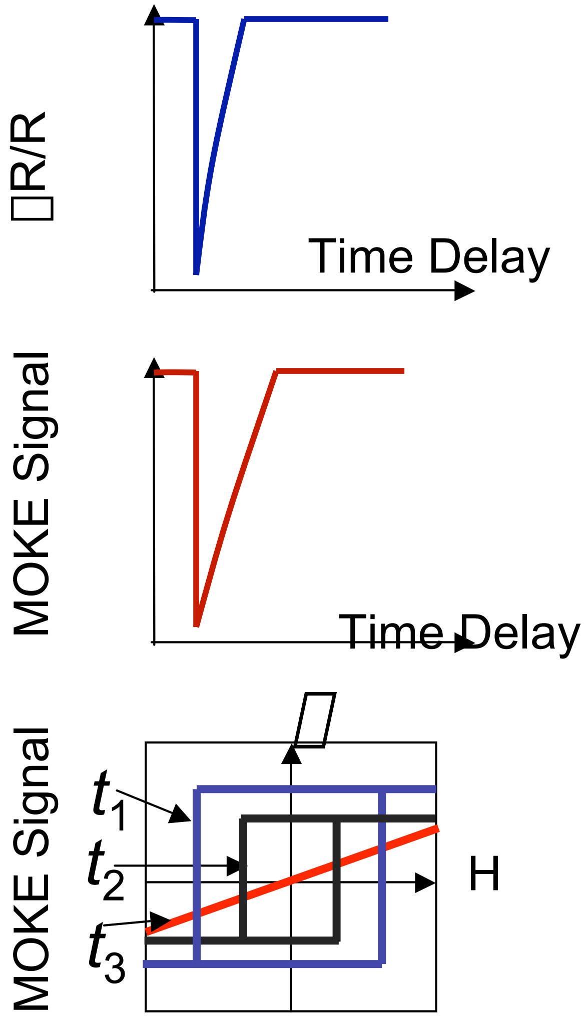
signal
1.1 μm to 1.6 μm
idler
1.6 μm to 3 μm

Difference Frequency Generator

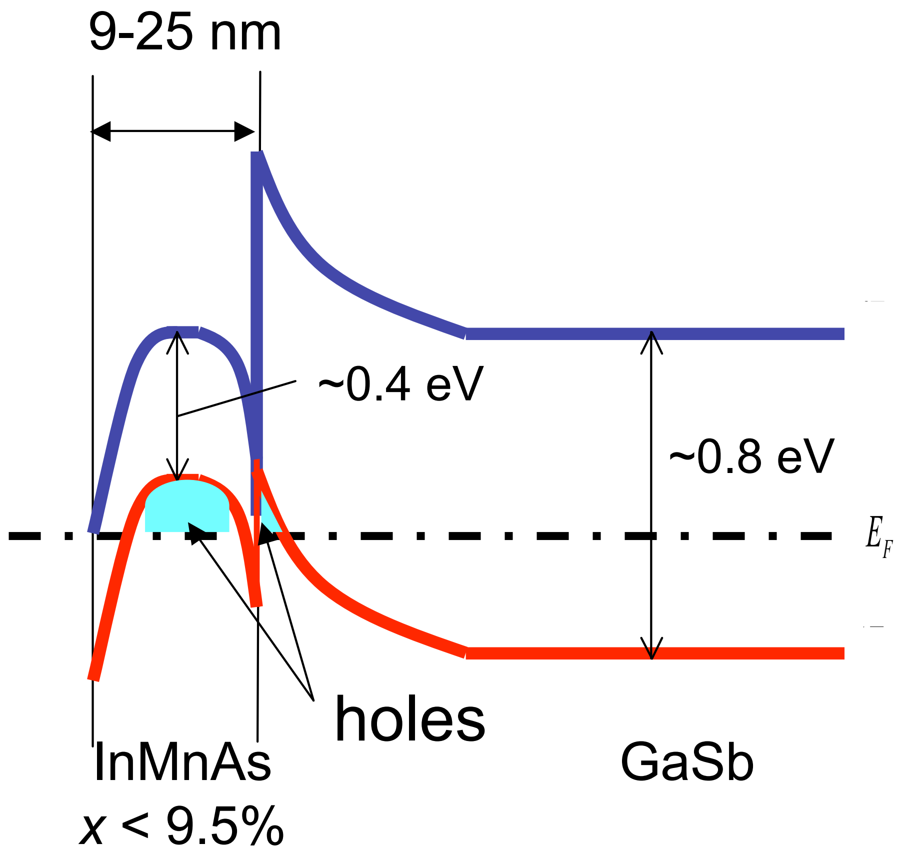
PRB **65**, 121307(R) (2002)
PRL **86**, 3292 (2001)
PRL **85**, 3293 (2000)

Experimental Setup



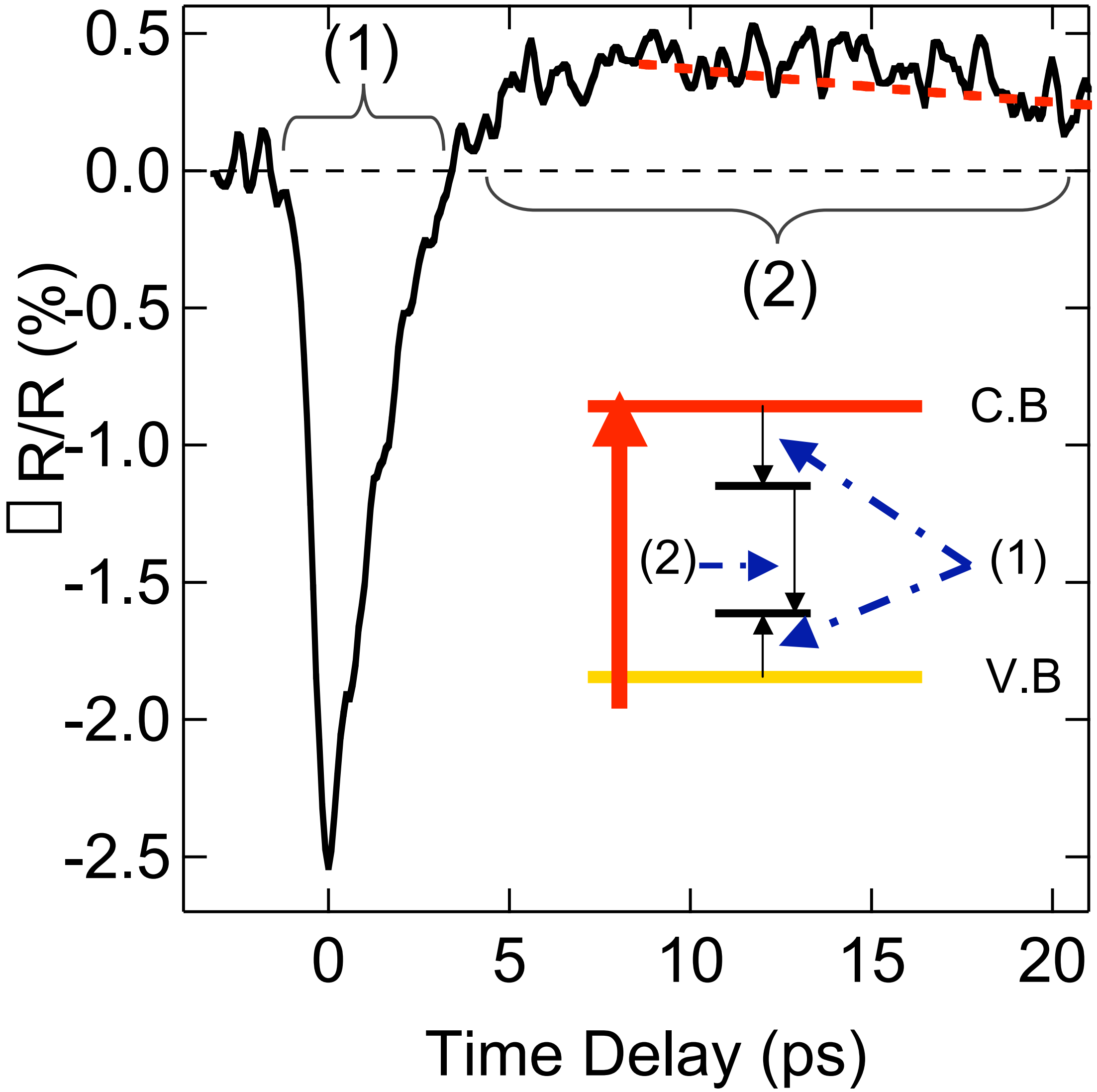


InMnAs-Based Heterostructures



- **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



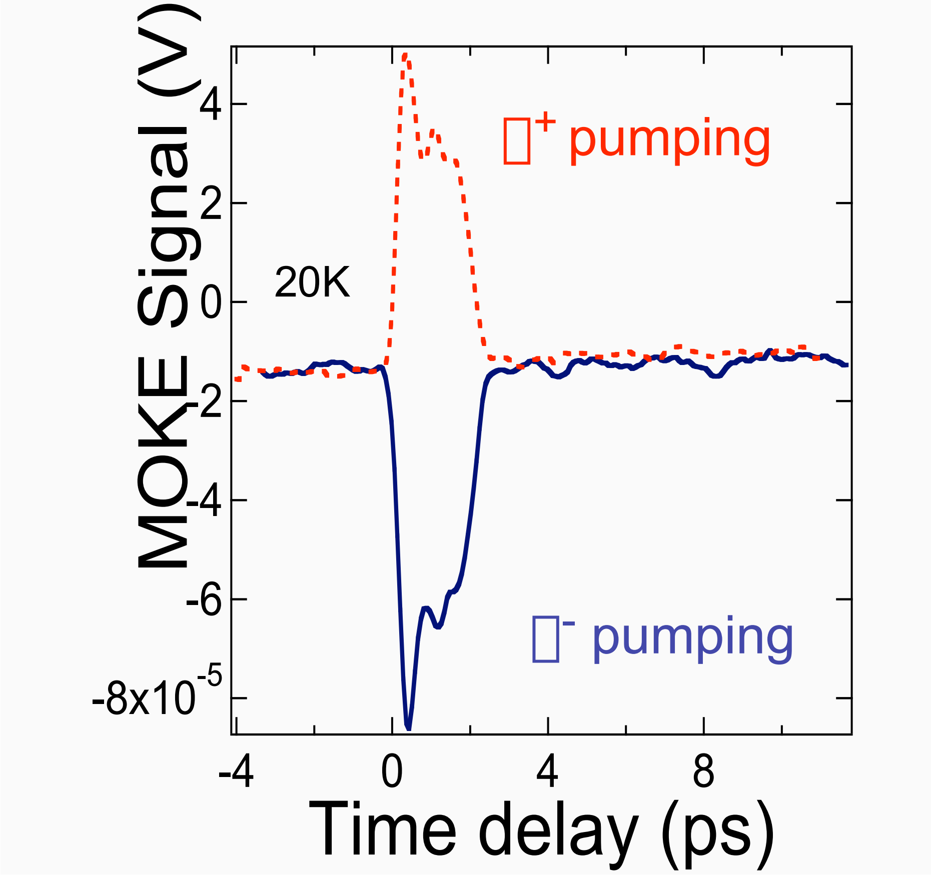
(1) carrier trapping

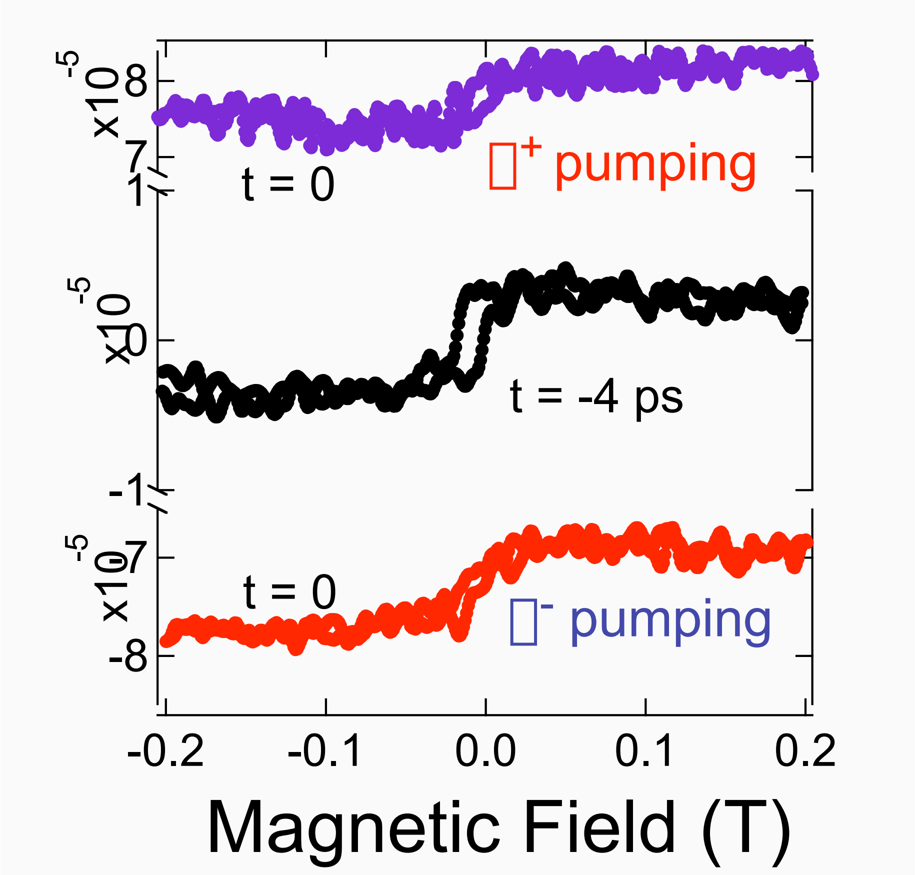
(~ 2 ps)

(2) recombination
of trapped
carriers

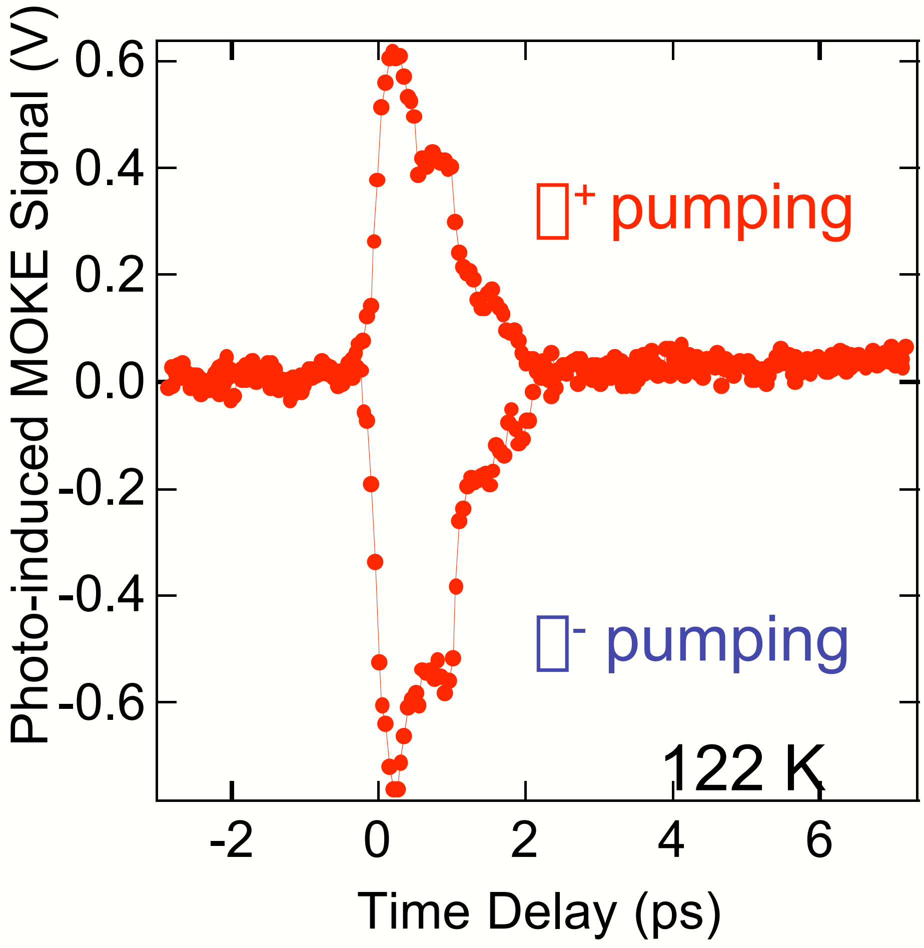
Pump 2 μm, 0.5 mW
Probe 775 nm

Pump-Polarization Dependence





MOKE Dynamics above T_c



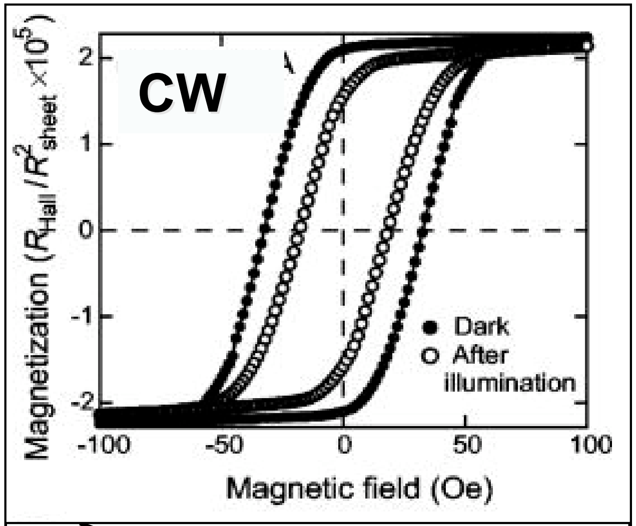
→ Not related to ferromagnetism
→ This is due to **carrier spin**

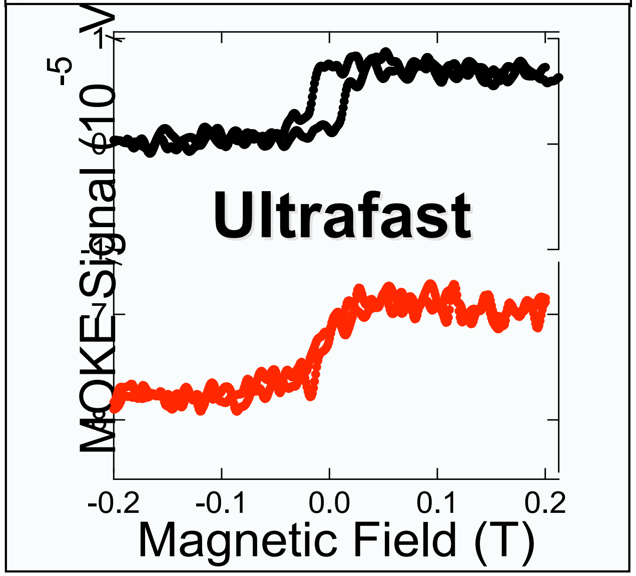
Origin of Ultrafast Softening

What determines coercivity?
-- Anisotropy & Exchange

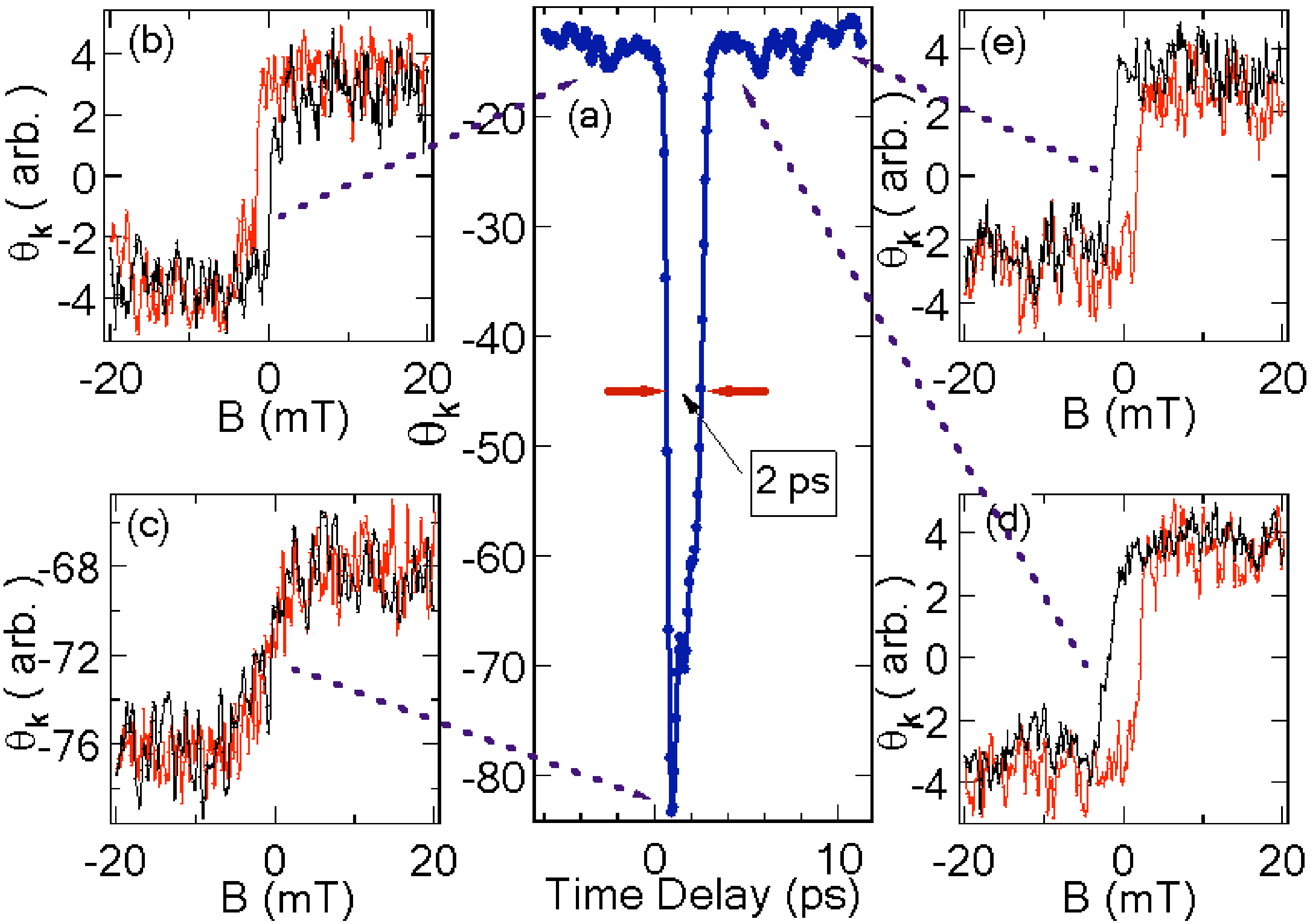
- Anisotropy (K) does NOT change with carrier density
- Exchange increases

Decreased domain wall energy
→ Smaller coercivity





Ultrafast Photoinduced Softening



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

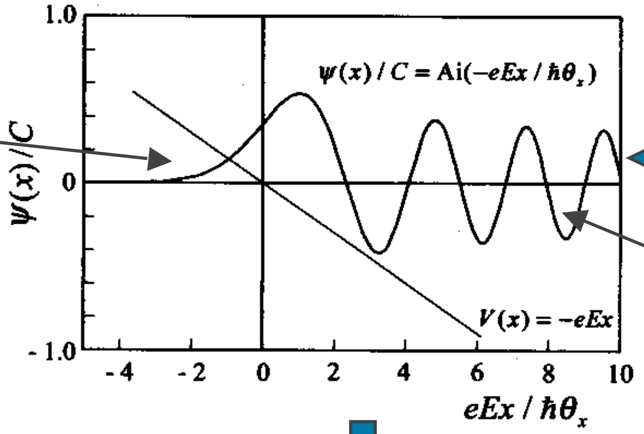
Franz-Keldysh Effect

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

Additional term in the Hamiltonian ⟶ $Ç' = \square e\vec{E}\cdot\vec{r}$

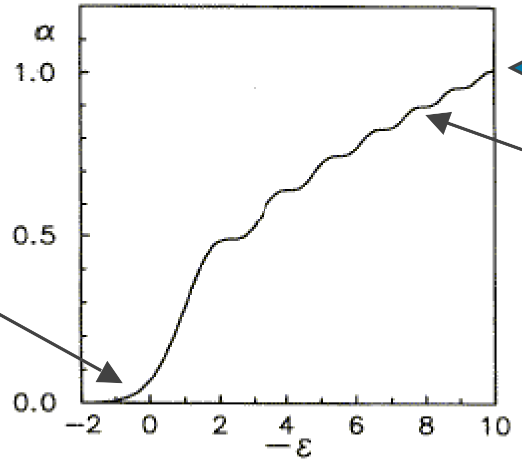
dc field

Exponential for positive arguments



wavefunction

Oscillations for negative arguments



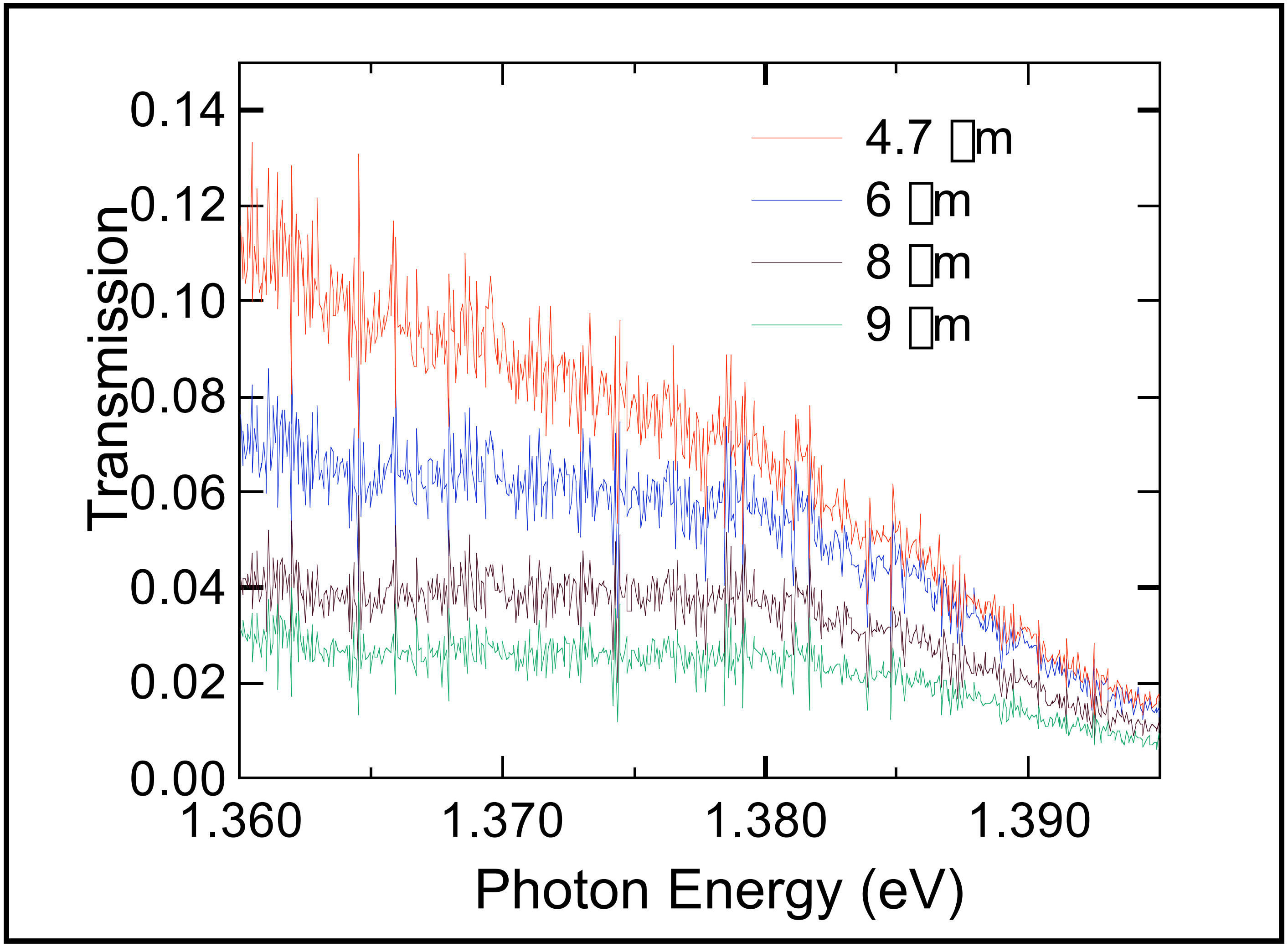
absorption

Exponential tail below bandgap

Oscillations above bandgap

Unusual Power Dependence

Below band gap absorption in bulk GaAs at 300 K

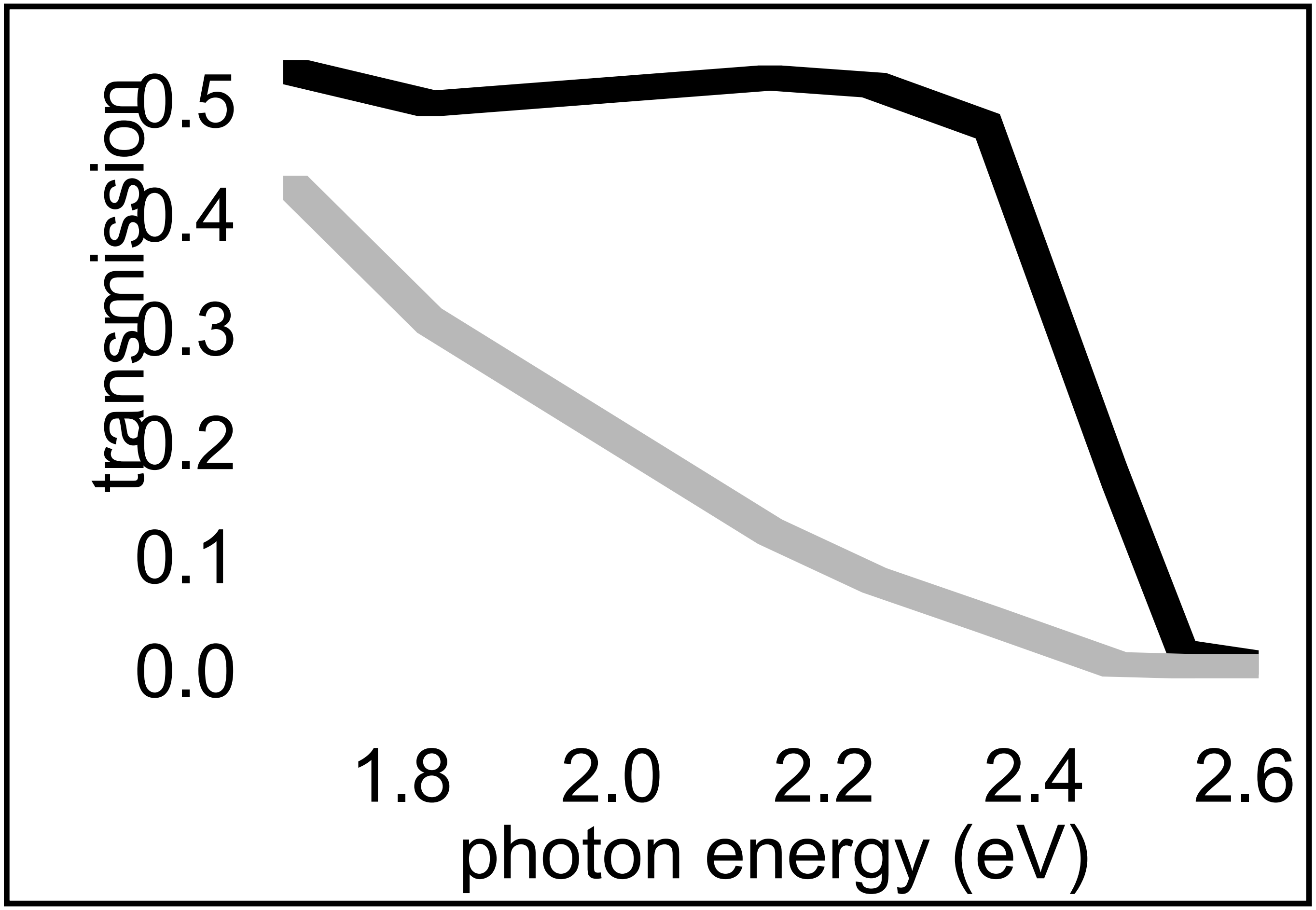


Decreasing intensity

Increasing effect!!

Extent of Induced Absorption

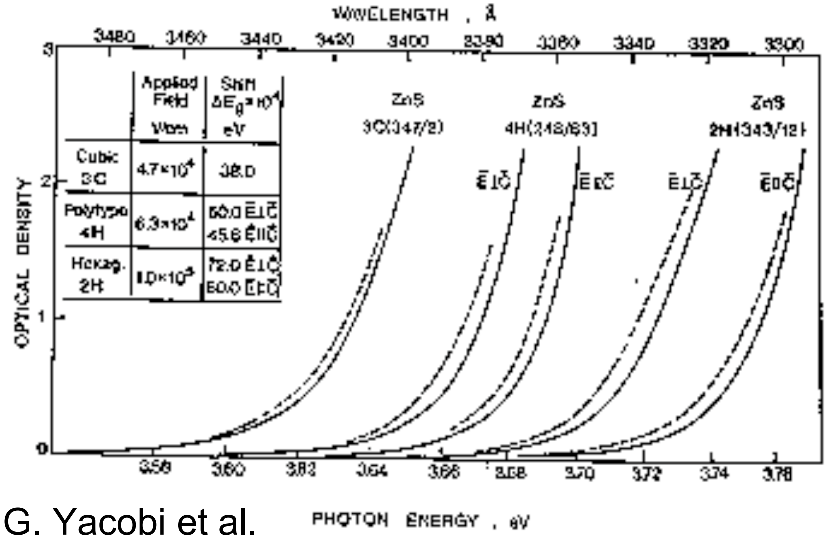
Polycrystalline ZnSe, 3.5 □m driving field, □~ 1



Induced absorption extends ***almost 1 eV*** below E_g!

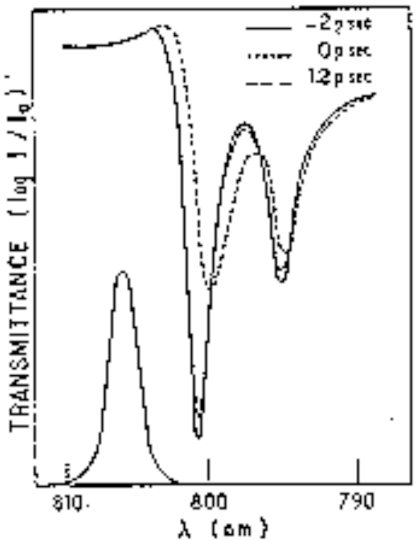
Other Strong-Field-Induced Effects in Semiconductors

DC Franz-Keldysh effect



B.G. Yacobi et al.

AC Stark effect



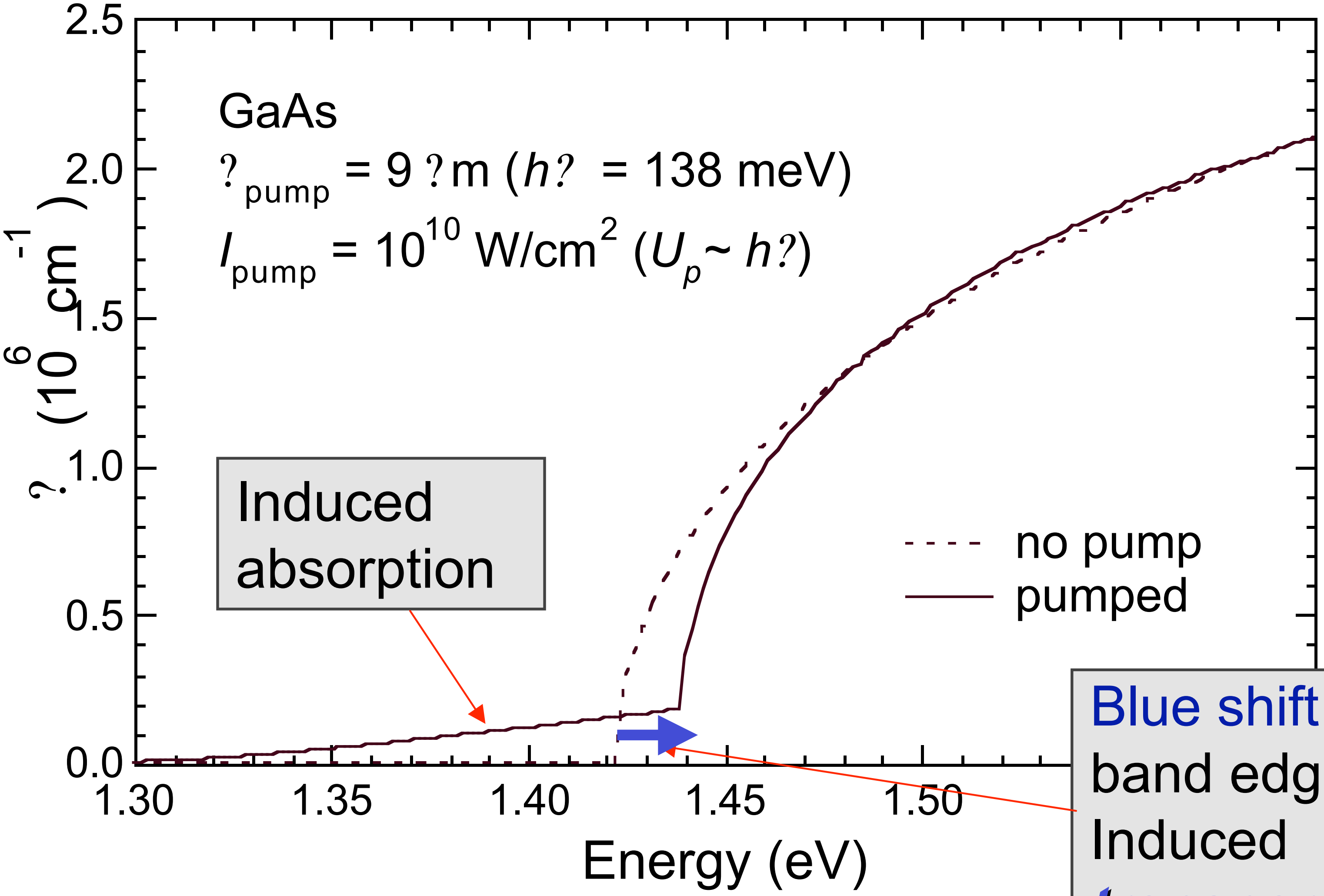
A. Mysyrowicz et al.

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

DFKE is a dramatic effect

DFKE Simulation for GaAs

Based on: Y. Yacoby, Phys. Rev. **169**, 610 (1967).

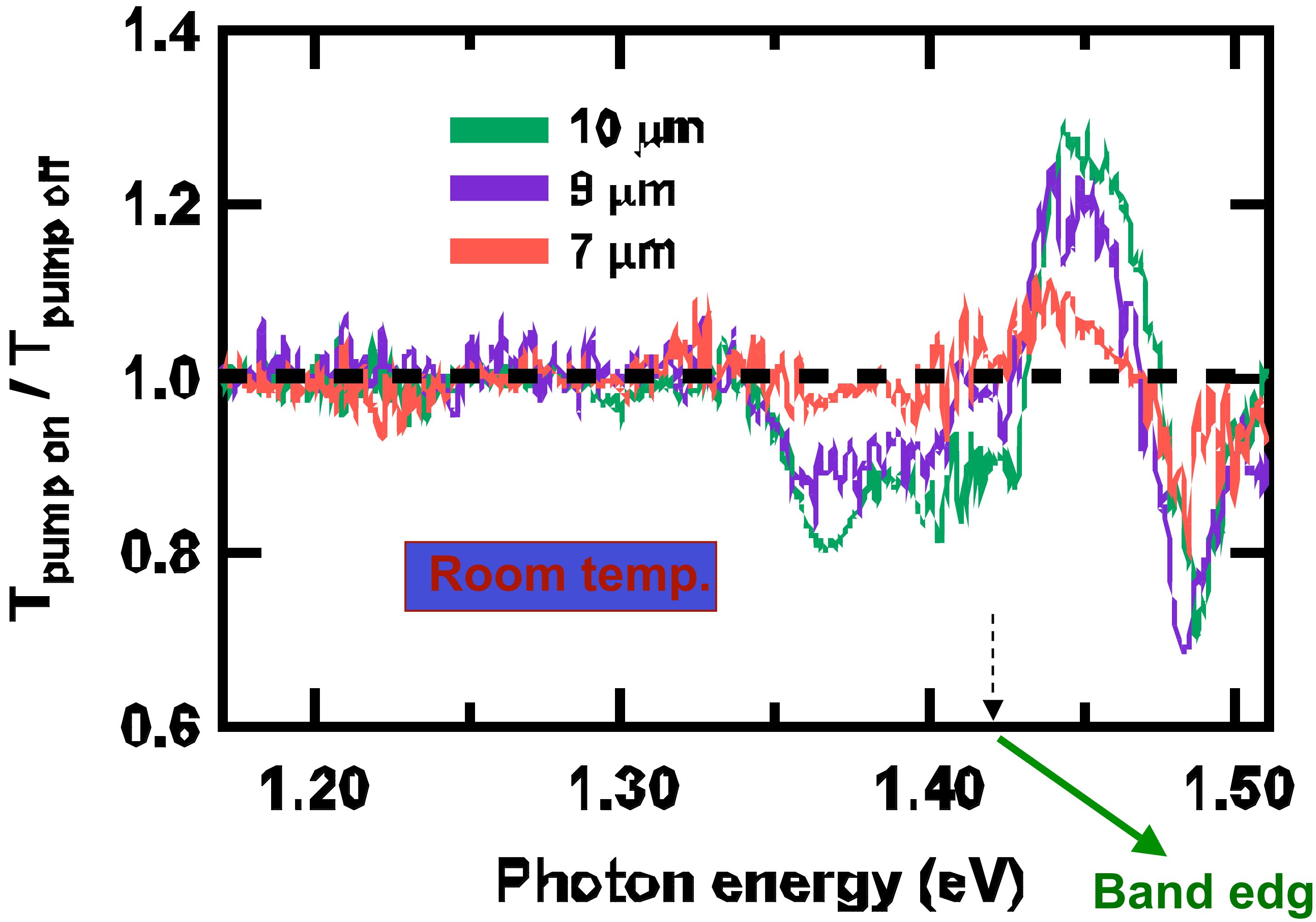


Induced absorption

Blue shift of band edge → Induced ***transparency***

Pump Wavelength Dependence

GaAs film



Band edge of GaAs

Experiments

- A. H. Chin, J. M. Bakker, and J. Kono, *Phys. Rev. Lett.* **85**, 3293 (2000).
- A. H. Chin, O. G. Calderón, and J. Kono, *Phys. Rev. Lett.* **86**, 3292 (2001).
- O. G. Calderón, A. H. Chin, and J. Kono, *Phys. Rev.* A **63**, 053807 (2001).
- M. A. Zudov, J. Kono, A. P. Mitchell, and A. H. Chin, *Phys. Rev.* B **64**, 121204(R), (2001).
- A. H. Chin, J. Kono, and G. S. Solomon, *Phys. Rev.* B **65**, 121307(R), (2002).
- A. Srivastava and J. Kono, in: *Quantum Electronics and Laser Science Conference*, OSA Technical Digest (Optical Society of America, Washington DC, 2003), QFD2.