Xray Magnetic Circular Dichroism Investigation in Ferromagnetic Semiconductors

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Condensed Matter National Lab-IPM
Novel 2D materials (Coordination of 32 international projects)

**Technology:**
- Energy production & storage
- Information technology
- Quantum electronics
- Construction materials
- Catalysts
- Novel coatings
- High-tech textiles
- Water desalination
- Medical treatments

**Fundamental science:**
- Plasmonics
- Surface charge transfer
- Mechanical properties
- Liquid crystals
- Valleytronics

**France:** CNRS, Sorbonnes Universities, ESPCI, Ecole Polytechnique, Universite Paris Sud, Institut Curie

**Denmark:** European Centre for Electron Nanoscopy

**Irland:** Trinity College Dublin

**Germany:** University of Paderborn

**Netherlands:** Groningen University

**Belgium:** University of Antwerp

**Australia:** IPIR, ISEM

**USA:** Massachusetts Institute of Technology

**China:** North-West university
Unified Information Storage and Processing Unit

(III-V semiconductors doped by transition metals)

Compatibility with currently used microelectronic technology

Magnetism control:
- Electrical control via charge density and wave function
- Optical control via spin-orbit coupling between photon angular momentum and carrier spins
- Structural control via strain
**How to make GaAs ferromagnetic?**

**P-type conductivity:** Mn$^{2+}$ acceptor + h

**Magnetic ions:** Mn$^{2+}$ S=5/2

**Magnetic coupling:** Zener kinetic exchange

\[
T_c \propto J^2_{pd} \cdot x_{Mn} \cdot p^{1/3}
\]

Intrinsic ferromagnetic phase with highest $T_c \sim 190$K

Intrinsic limit of Curie temperature in GaMnAs

- Thin solid films 519, 8212 (2010)
- K. Khazen PhD thesis
Room Temperature Ferromagnetic Ga$_{1-x}$Mn$_x$As?

External control of magnetic order: **Interlayer coupling**

Maccherozzi et al, PRL 2008

2nm
Room Temperature Ferromagnetic Ga$_{1-x}$Mn$_x$As?

External control of magnetic order: **Interlayer coupling**

Detailed magnetic properties investigations:

- Magnetic resonance
- Magnetometry
- XPS
- X-ray diffraction and reflection
- Ion beam analysis
- Spin polarized neutron reflectivity
- XMCD

Maccherozzi et al, PRL 2008
Room temperature Ferromagnetic $\text{Ga}_{1-x}\text{Mn}_x\text{As}$?

A. Two step layer growth

LPN-Alcatel, Simon Fraser Univ
Room temperature Ferromagnetic Ga$_{1-x}$Mn$_x$As?

A. Two step layer growth
LPN-Alcatel, Simon Fraser Univ

Landau-Lifshtiz:

$H_{microwave}$

$M$

$\frac{dM}{dt} = -\gamma [(M \times (H + H_{eff}))]$

$H_{eff} \propto K_{anisotropy}$

Polycrystalline Fe and single crystalline GaMnAs
Presence of second phase superparamagnetic particles in the interface
Room temperature Ferromagnetic Ga$_{1-x}$Mn$_x$As?

B. One step layer growth

Epitaxial growth of Fe over GaMnAs
Room temperature Ferromagnetic Ga$_{1-x}$Mn$_x$As?

B. One step layer growth

Nottingham

Epitaxial growth of Fe over GaMnAs

No second phase formation
The interface magnetism and its origin cannot be studied via FMR
XMCD spectroscopy

Sharp increases in **X-ray Absorption** coefficient:

**Absorption edges** → Transferring low energy bound electrons to empty states just above the Fermi energy

![Energy level diagram](image-url)
XMCD spectroscopy

Circularly polarized photons → Angular momentum transfer to electrons

Attenuation coefficient dependence on the relative orientation of the photon helicity and sample magnetization
XMCD spectroscopy

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Attenuation coefficient dependence on the relative orientation of the photon helicity and sample magnetization

Allowed transitions

\[ l = \pm 1 \] and \[ m = \pm 1 \] and \[ m_s = 0 \]
XMCD spectroscopy

Circularly polarized photons → Angular momentum transfer to electrons

Attenuation coefficient dependence on the relative orientation of the photon helicity and sample magnetization

Allowed transitions

\[ l = \pm 1 \text{ and } m = \pm 1 \text{ and } m_s = 0 \]

Difference in right and left-handed polarized XA
XMCD spectroscopy

Main detection techniques:

(i) Auger decay: an intermediate electron drops into the hole and the liberated energy results in the ejection of another electron

(ii) Fluorescent decay: where the photoelectron generated by the absorption event recombines with the hole left behind re-emitting an x-ray photon
XMCD spectroscopy

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As each detected particle originates from different spatial region

Attenuation length of Xray, for (Ga,Mn)As=561 nm

Escape depth of electrons $\lambda = \frac{-2}{ln(1 - k)} = 2.9$nm
XMCD at the Mn L2,3 edge

Diamond Light Source, I06 beamline

Experiments led by Kevin Edmonds, James Heigh and Peter Wadely
PhD thesis
XMCD at the Mn L2,3 edge

Diamond Light Source, I06 beamline

Conditions:
- Room temperature measurements
- TEY detection

- A small but clear Mn-related peak observed at room temperature
- Comparison of the peak with reference, Mn, FeMn, MnAS, etc, revealed that it is a localized Mn\(^{2+}\) localized state
XMCD at the Mn L2,3 edge

Diamond Light Source, I06 beamline

Conditions:
- $T=2\,\text{K}$ measurements
- TEY and FY detection
- Attenuation
- Anti-parallel alignment of the Mn moment at $H=0$
- Signal from the surface shows frustration
- Proposed model: proximity polarisation of the Mn ions near to the Fe layer
- Thickness of the strongly coupled layer of $x = 0.9\,\text{nm}$

K. Olejnik et al, PRB 2010
Take-home message...

- **Element-resolved** character, **nano/micro spatial resolution**, and possibility to distinguish **spin/orbital contributions** important role in novel magnetic system development

- But, it should be noted that using synchrotron based techniques should be **justified**.

- **Not limited** to conventional and classic techniques available at the beamlines. much more to be explored!