Carrier and Spin Injection in ZnMnSe/CdSe Nanostructures

D. Dagnelund, I.A. Buyanova, T. Furuta¹, K. Hyomi¹, I. Souma¹, A. Murayama¹, and W.M. Chen

Department of Physics, Chemistry and Biology, Linköping University, 581 83 Linköping, Sweden

¹Institute of multidisciplinary Research for Advanced Materials, Tohoku University, Sendai, 980-8577, Japan
Spin-dependent electronics (Spintronics):
utilizes spin to sense, store and process information

Applications:
- Information storage
- Information processing
- Communications

Advantages: high density, high speed, low power, new functionality
Introduction and Motivation: Semiconductor spintronics

Key components:
- Spin alignment
- Spin injection
- Spin manipulation
- Spin detection

Desired spin injectors and detectors:
- Compatible with the rest of spintronic devices
- Efficient spin injection and detection (or readout)
Introduction and Motivation: Semiconductor spintronics

- **Suitable spin injectors: Dilute magnetic semiconductors (DMS)**
  - II-Mn-VI based DMS, e.g. (Zn,Cd,Mn)(Se,Te)
    - Advantage: Mature growth techniques, good understanding of magnetism
    - Disadvantage: Magnetic at low temperatures
  - (Ga,In,Mn)As based DMS
    - Advantage: Improved knowledge, existing (Ga,In)As-based devices
    - Disadvantage: Ferromagnetic only at low temperatures
  - DMS based nitrides and oxides
    - Advantage: Ferromagnetic at room temperature
    - Disadvantage: Poor material quality, poor understanding of magnetism

- **Compatible spin detectors: Nonmagnetic semiconductors**
  - (Zn,Cd)(Se,Te)
  - (In,Ga)As
  - (In,Ga)N, (Zn,Cd)O
Introduction and Motivation:
Limited spin injection efficiency - Problems

Why Limited spin injection efficiency?

- Incomplete spin alignment in DMS?
- Spin scattering during spin injection?
- Spin depolarization in spin detector?

Semiconductor quantum dots as a spin detector by taking advantage of slower spin relaxation?
Growth method: Molecular beam epitaxy

Spin Injector: Zn$_{0.93}$Mn$_{0.07}$Se

Spin Detector: Self-assembled CdSe QD’s

Substrate: (100) GaAs
Experimental Approach

- Resonant generation of spin-polarized excitons in the DMS, leading to complete spin alignment

- Spin loss during spin injection

-Selective detection of spin-polarized excitons in the QD’s, determining spin loss

Tunable laser excitation

Polarized PL detection
Photoluminescence

Micro-PL
(referent sample)

Macro-PL

PL intensity (a.u.)

Photon energy (eV)

DMS
ZnSe

PL intensity (arb. units)

Photon energy (meV)

QD’s

4.2 K, 0 T

15 x
Excitation of Polarized PL

- **PL excitation (PLE) spectra of QD:**
  - DMS peak
  - Carrier injection from DMS to QD

- **Below DMS excitation:**
  - $P_{\text{int}} = (\sigma^+ - \sigma^-)/(\sigma^+ + \sigma^-) < 0$
  - Intrinsic properties of QD’s

- **Resonant DMS excitation:**
  - $P = (\sigma^+ - \sigma^-)/(\sigma^+ + \sigma^-) > 0$
  - Spin injection from DMS
Carrier and spin injection: Dependence on barrier thickness

- **Carrier injection from DMS:**
  - Efficient, independent on barrier thickness $L_b$

- **Spin injection from DMS**
  - Strong dependence on $L_b$

Origin?
Possible mechanisms for carrier injection:

- **Tunneling:**
  - Strong dependence on barrier thickness, $\sim \exp(-L_b)$

- **Dipole-dipole interaction:**
  - Strong dependence on $L_b$, $\sim L_b^{-4}$

- **Photon-exchange:**
  - Weak dependence on $L_b$
    - Consistent with experiment
Spin Injection: Rate Equation Analysis

\[
\begin{align*}
\frac{dN^+_{QD}}{dt} &= G + K \gamma N^+_{DMS} - \frac{N^+_{QD}}{\tau_t^{QD}} - \frac{N^+_{QD}}{\tau_r^{QD}} - \frac{N^+_{QD}}{\tau_s^{QD}(1 + e^{-\Delta E/kT})} + \frac{N^-_{QD}}{\tau_s^{QD}(1 + e^{\Delta E/kT})}, \\
\frac{dN^-_{QD}}{dt} &= G + (1-K) \gamma N^+_{DMS} - \frac{N^-_{QD}}{\tau_t^{QD}} - \frac{N^-_{QD}}{\tau_r^{QD}} + \frac{N^+_{QD}}{\tau_s^{QD}(1 + e^{-\Delta E/kT})} - \frac{N^-_{QD}}{\tau_s^{QD}(1 + e^{\Delta E/kT})}
\end{align*}
\]

\( K \equiv \frac{N^+_{injected}}{N^+_{DMS}} \), spin conservation factor

\[
P = \frac{1 - e^{\Delta E/kT}}{1 + e^{\Delta E/kT}} + \frac{2K - 1}{1 + \frac{G}{\gamma N^+_{DMS}} + 1 + \frac{\tau_r^{QD}}{\tau_s^{QD}}} \]

Parameters?
Spin Injection: Time-resolved Polarized PL

PL transient:

Rate Equation Analysis:

- Radiative and spin-flip times in QDs are independent of $L_b$.
- Spin loss during energy transfer increases with $L_b$.
  - Spin scattering in the barrier?
  - Changes in interface quality with $L_b$?
Summary

- **Direct evidence for spin injection from Zn$_{0.93}$Mn$_{0.07}$Se DMS to CdSe QD’s**
  - Tunable laser excitation

- **Determination of the dominant mechanism for carrier injection during spin injection**
  - Energy transfer via photon exchange

- **Spin loss during spin injection**
  - Strong dependence on barrier width
  - Origin unknown so far
  - Further experimental and theoretical studies required