Carrier and Spin Injection in ZnMnSe/CdSe Nanostructures

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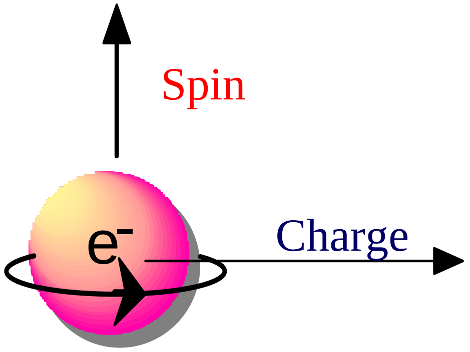
Introduction and Motivation:
Spintronics

Spin-dependent electronics (Spintronics):

utilizes spin to sense, store and process information

Applications:

- Information storage
- Information processing
- Communications



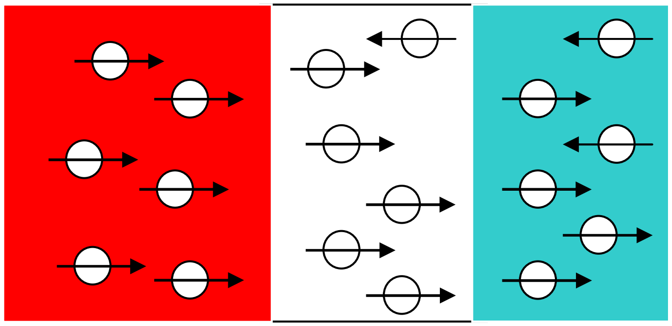
Advantages: high density, high speed, low power, new functionality

Introduction and Motivation:

Semiconductor spintronics

➢ Key components:

- Spin alignment
- Spin injection
- Spin manipulation
- Spin detection



Spin injector (e.g DMS)

Spin detector

➢ Desired spin injectors and detectors:

- Compatible with the rest of spintronic devices
- Efficient spin injection and detection (or readout)

Introduction and Motivation:

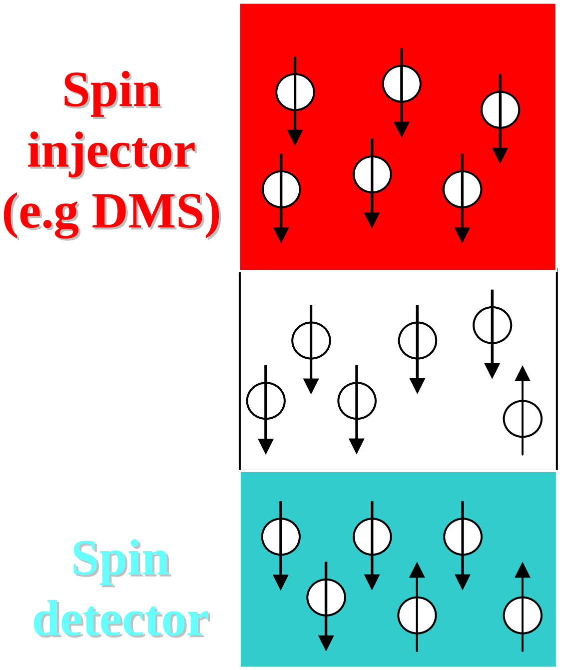
Semiconductor spintronics

- **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

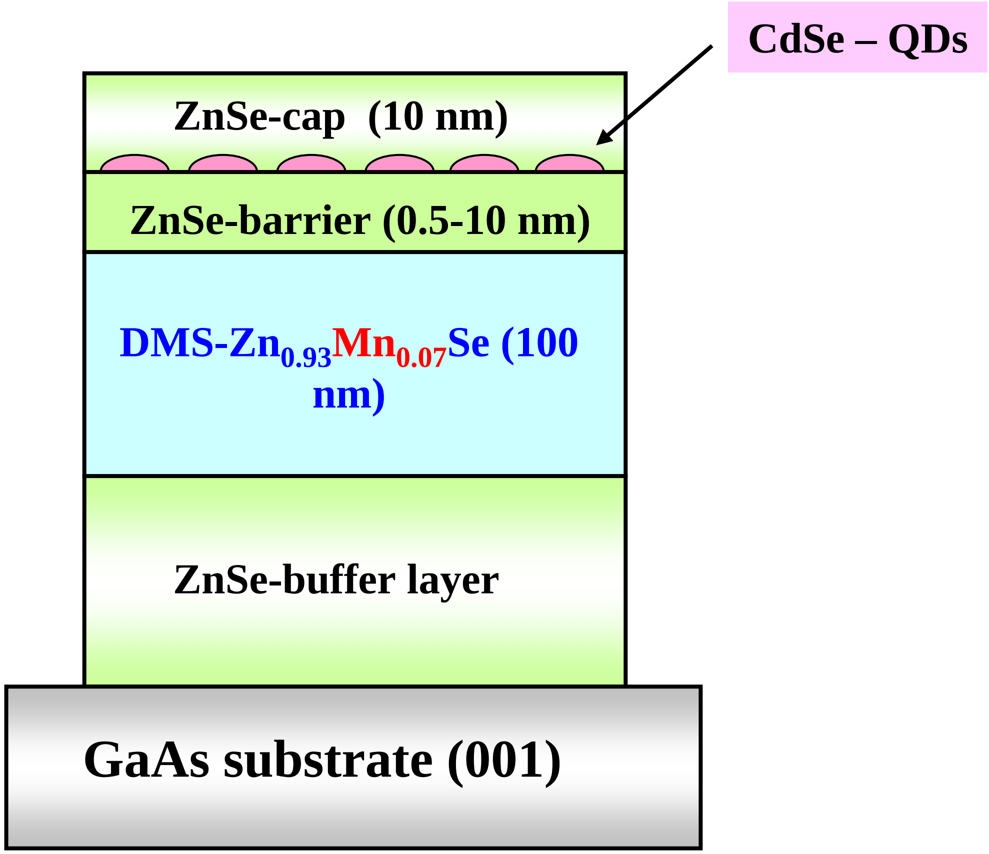
Why Limited spin injection efficiency ?



- 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 ?

Samples



CdSe – QDs

ZnSe-cap (10 nm)

ZnSe-barrier (0.5-10 nm)

DMS-$Zn_{0.93}Mn_{0.07}Se$ (100 nm)

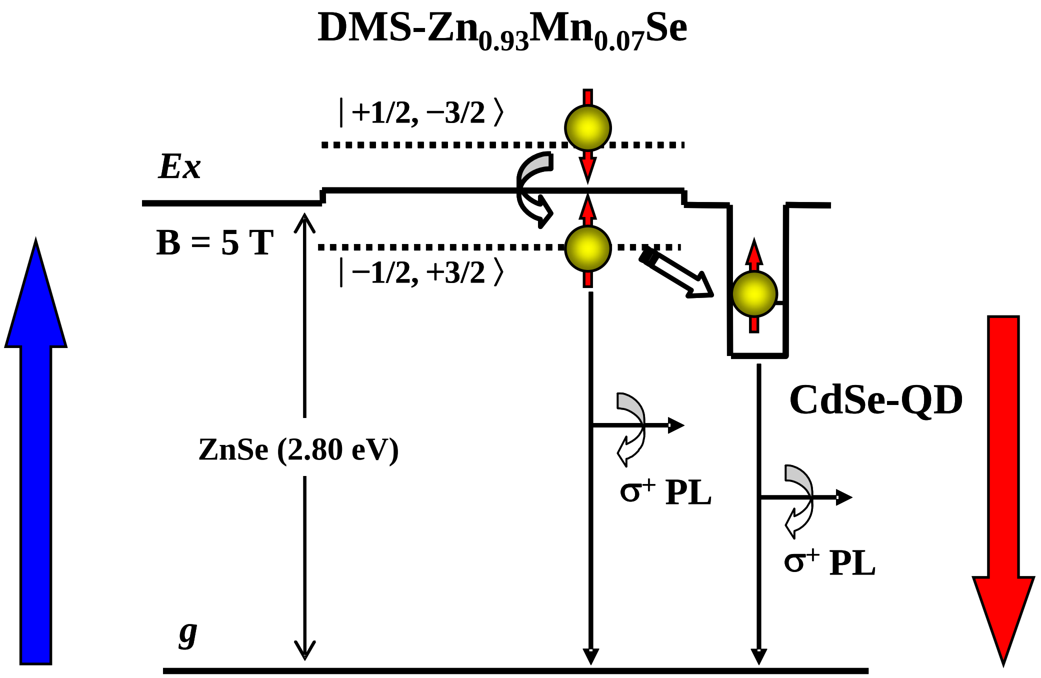
ZnSe-buffer layer

GaAs substrate (001)

- ❑ **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

Tunable laser excitation



Polarized PL detection

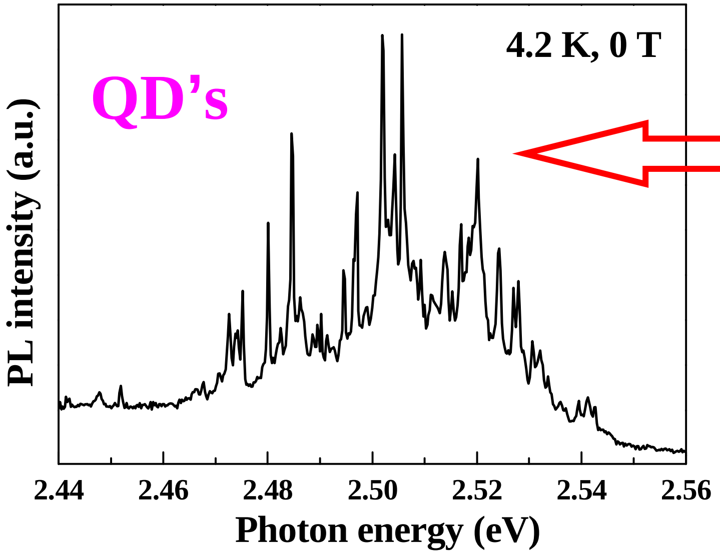
- ➢ Resonant generation of spin-polarized excitons in the DMS, leading to **complete spin alignment**

- ➢ Spin loss during spin injection

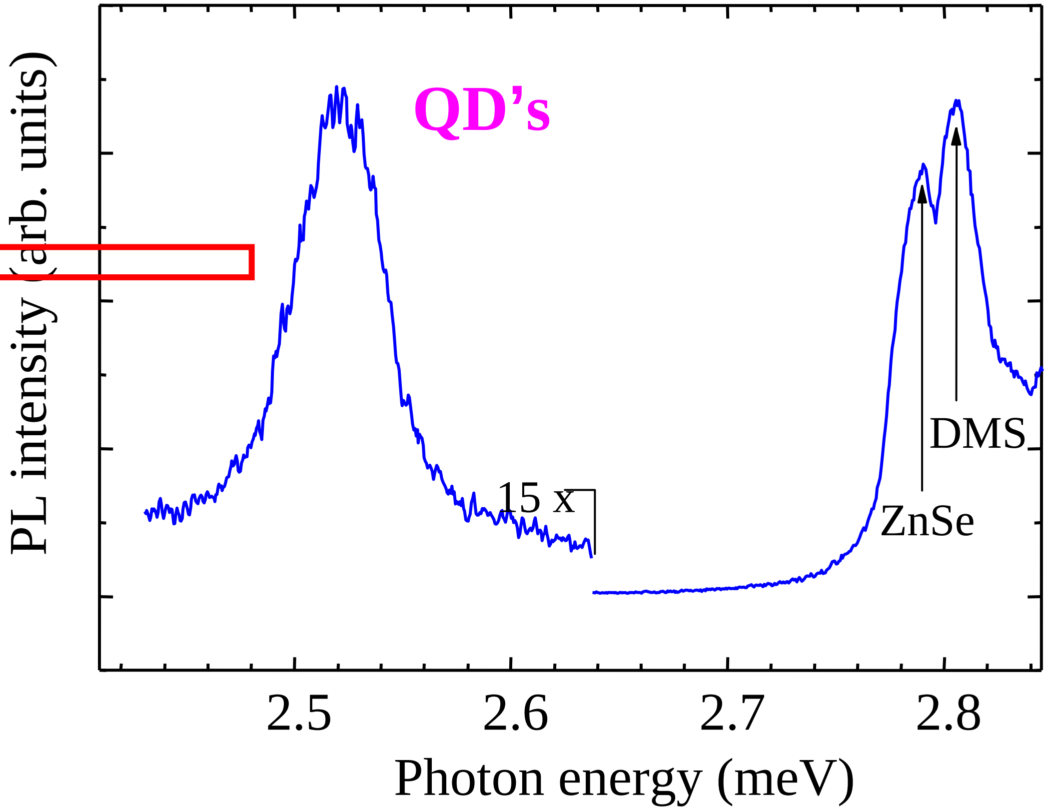
- ➢ Selective detection of spin-polarized excitons in the QD’s, **determining spin loss**

Photoluminescence

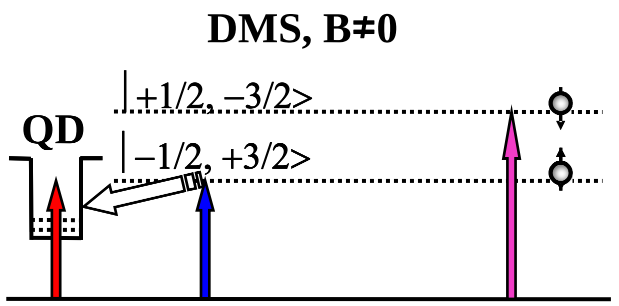
Micro-PL
(reference sample)

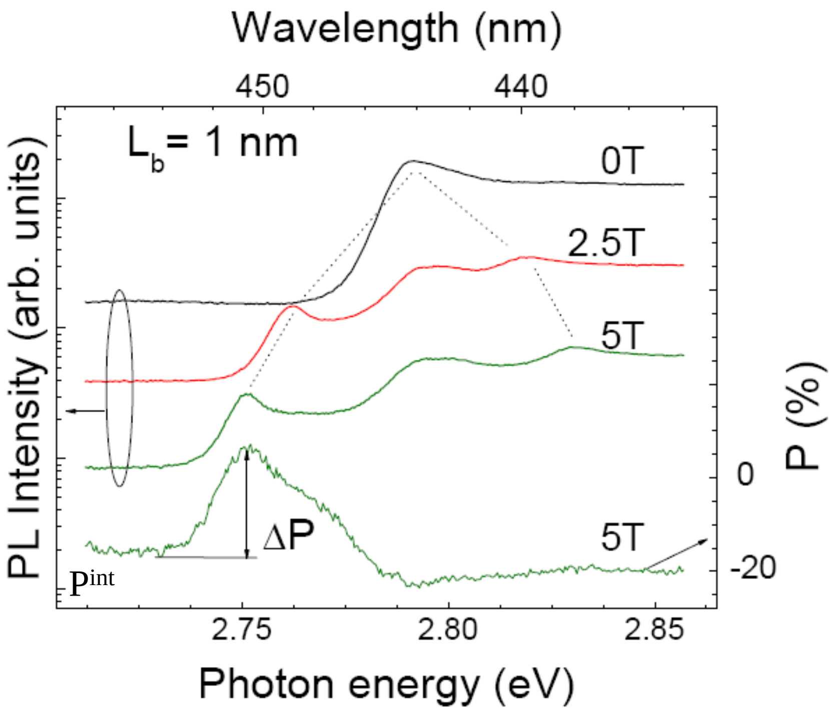


Macro-PL



Excitation of Polarized PL





❑ **PL excitation (PLE) spectra of QD:**

- **DMS peak**
  - ➢ **Carrier injection from DMS to QD**

❑ **Below DMS excitation:**

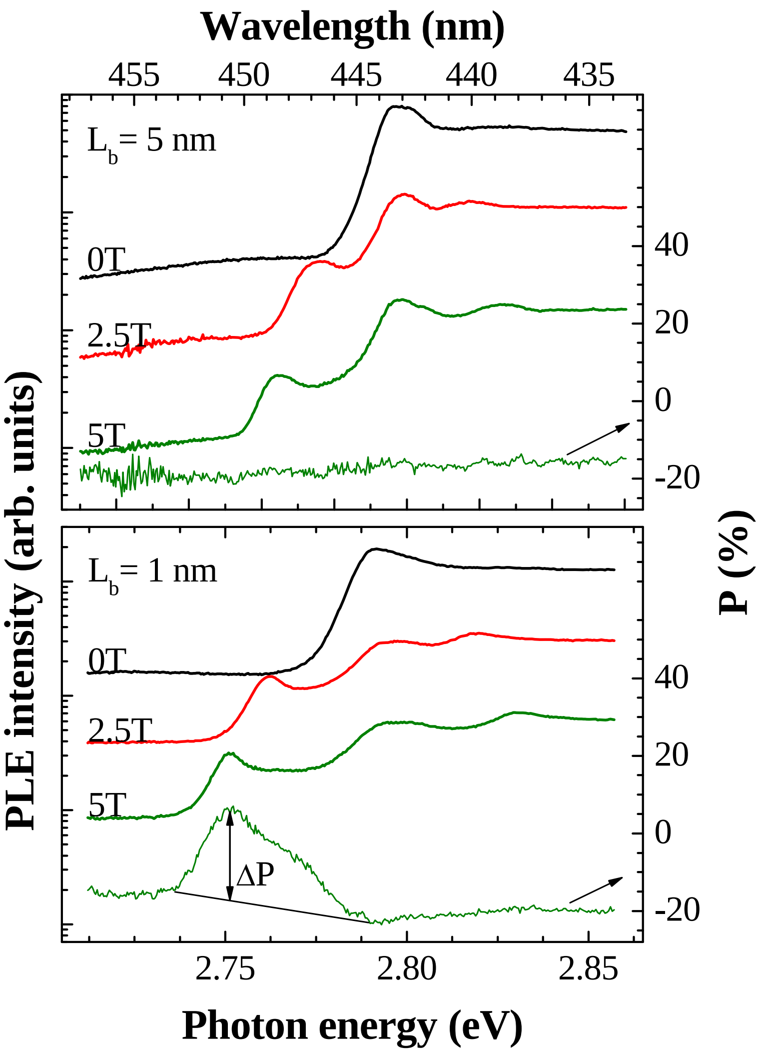
- **$P^{int}=(\sigma^{+}-\sigma^{-})/(\sigma^{+}+\sigma^{-}) < 0$**
  - ➢ **Intrinsic properties of QD's**

❑ **Resonant DMS excitation:**

- **$P=(\sigma^{+}-\sigma^{-})/(\sigma^{+}+\sigma^{-})$ ⇗**

  ➡ **$\Delta P=P-P^{int}>0$**
  - ➢ **Spin injection from DMS**

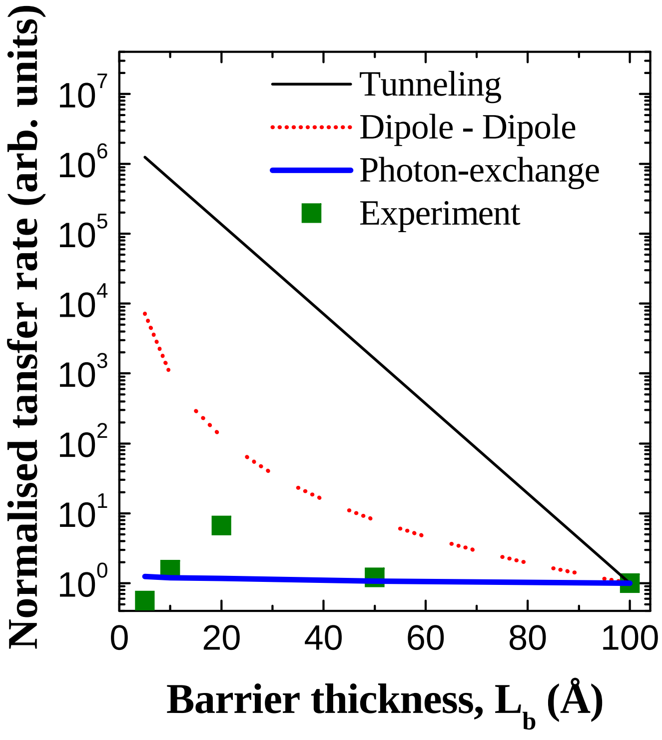
Carrier and spin injection: Dependence on barrier thickness



- ☐ **Carrier injection from DMS:**
  - **Efficient, independent on barrier thickness L_b**
- ☐ **Spin injection from DMS**
  - **Strong dependence on L_b**

Origin?

Carrier injection: Mechanism



Possible mechanisms for carrier injection:

☒ **Tunneling:**

- **Strong dependence on barrier thickness, ~ exp(-L_b)**

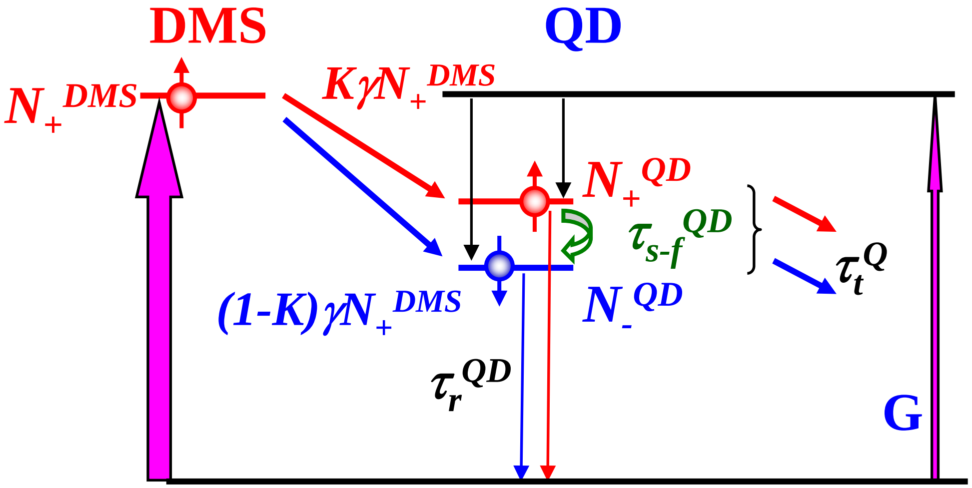
☒ **Dipole-dipole interaction:**

- **Strong dependence on L_b, ~ L_b^{-4}**

☑ **Photon-exchange:**

- **Weak dependence on L_b**
  - ➢ **Consistent with experiment**

Spin Injection: Rate Equation Analysis



$$\frac{dN_+^{QD}}{dt}=G+K\gamma N_+^{DMS}-\frac{N_+^{QD}}{\tau_t^{QD}}-\frac{N_+^{QD}}{\tau_r^{QD}}-\frac{N_+^{QD}}{\tau_{s-f}^{QD}(1+e^{-\Delta E/kT})}+\frac{N_-^{QD}}{\tau_{s-f}^{QD}(1+e^{\Delta E/kT})}$$

$$\frac{dN_-^{QD}}{dt}=G+(1-K)\gamma N_+^{DMS}-\frac{N_-^{QD}}{\tau_t^{QD}}-\frac{N_-^{QD}}{\tau_r^{QD}}+\frac{N_+^{QD}}{\tau_{s-f}^{QD}(1+e^{-\Delta E/kT})}-\frac{N_-^{QD}}{\tau_{s-f}^{QD}(1+e^{\Delta E/kT})}$$

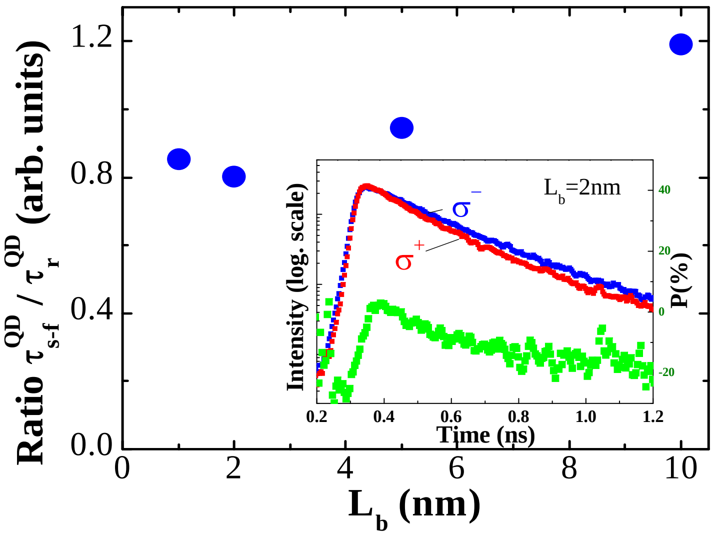
$K \equiv N_+^{injected}/N_+^{DMS}$, spin conservation factor

$$P=\underbrace{\frac{\dfrac{1-e^{\Delta E/kT}}{1+e^{\Delta E/kT}}}{1+\dfrac{\tau_{s-f}^{QD}}{\tau_r^{QD}}}}_{INTRINSIC}+\boxed{\underbrace{\frac{2K-1}{\left(1+\dfrac{G}{\gamma N_+^{DMS}}\right)\left(1+\dfrac{\tau_r^{QD}}{\tau_{s-f}^{QD}}\right)}}_{DMS-INDUCED=\Delta P}}$$

Parameters?

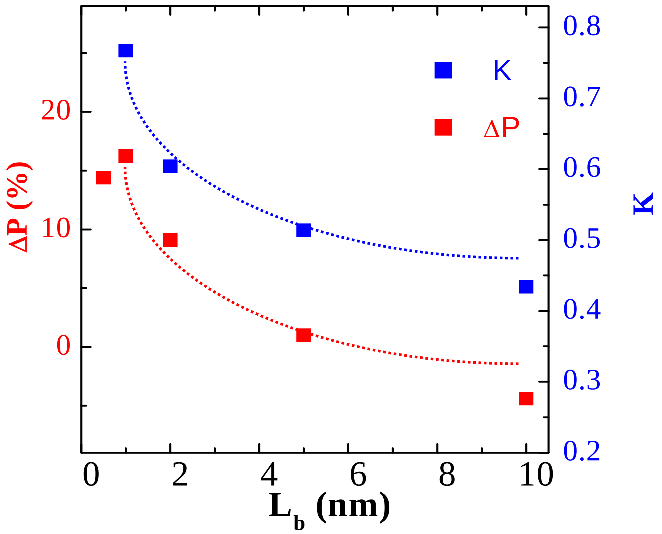
Spin Injection: Time-resolved Polarized PL

PL transient:



- ➢ Radiative and spin-flip times in QDs are independent of L_b

Rate Equation Analysis:



- ➢ 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**