



Carrier and Spin Injection in ZnMnSe/CdSe Nanostructures

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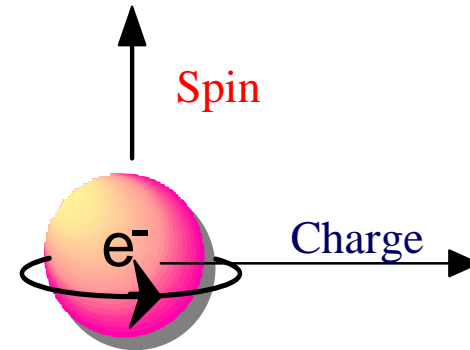
Introduction and Motivation: Spintronics

Spin-dependent electronics (Spintronics):

utilizes spin to sense, store and process information

➤ Applications:

- Information storage
- Information processing
- Communications



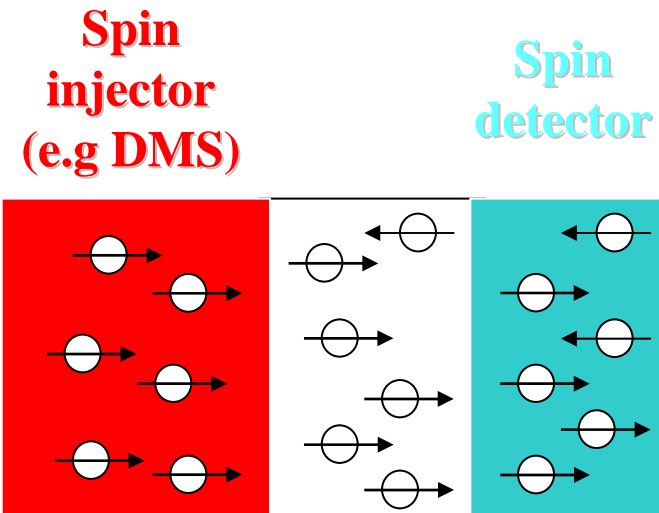
Advantages: high density, high speed, low power, new functionality



Introduction and Motivation: Semiconductor spintronics

➤ Key components:

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



➤ Desired spin injectors and detectors:

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

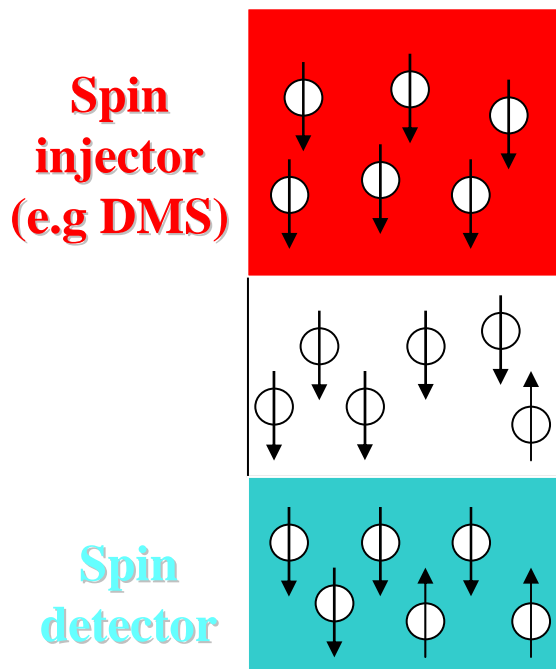


Introduction and Motivation: Semiconductor spintronics

- **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

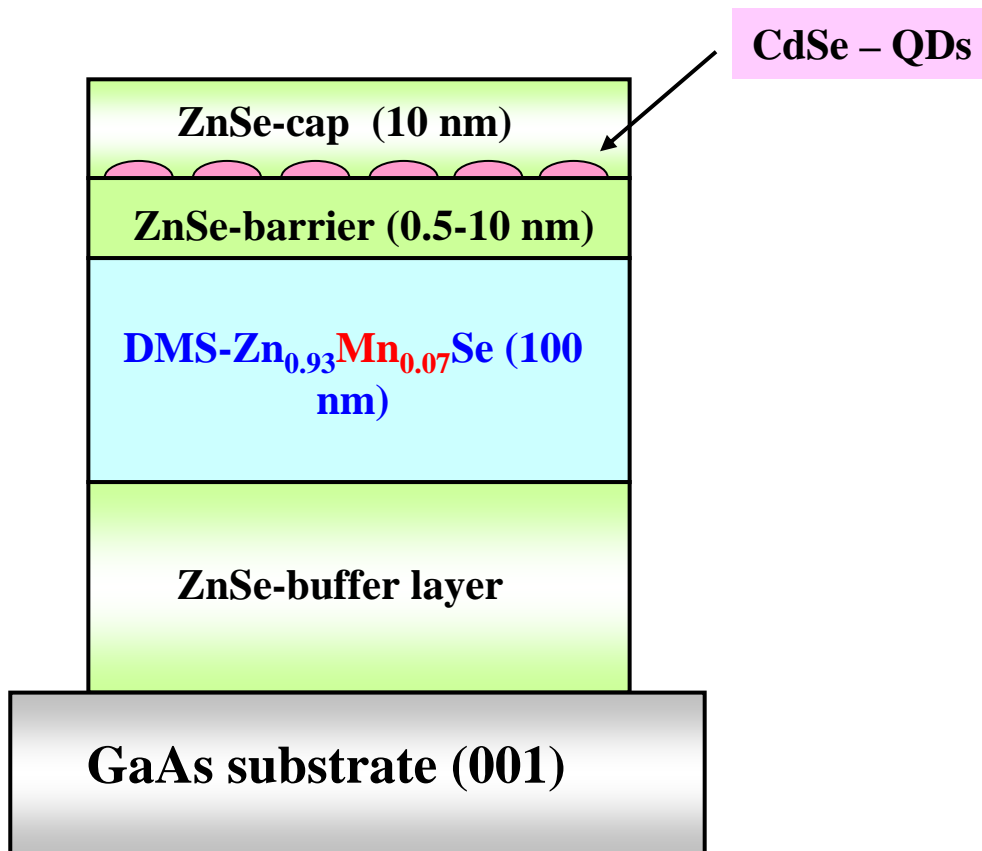
Why Limited spin injection efficiency ?



- 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 ?**

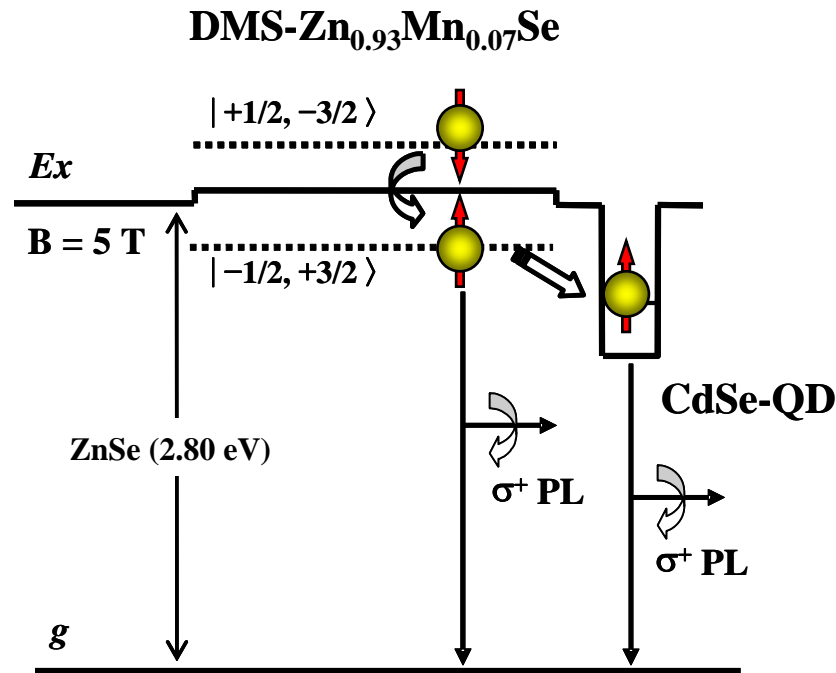
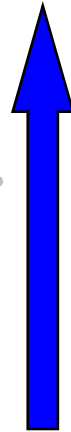
Samples



- ❑ **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

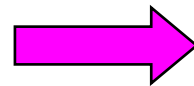
Tunable laser excitation



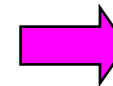
Polarized PL detection



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



➤ Spin loss during spin injection

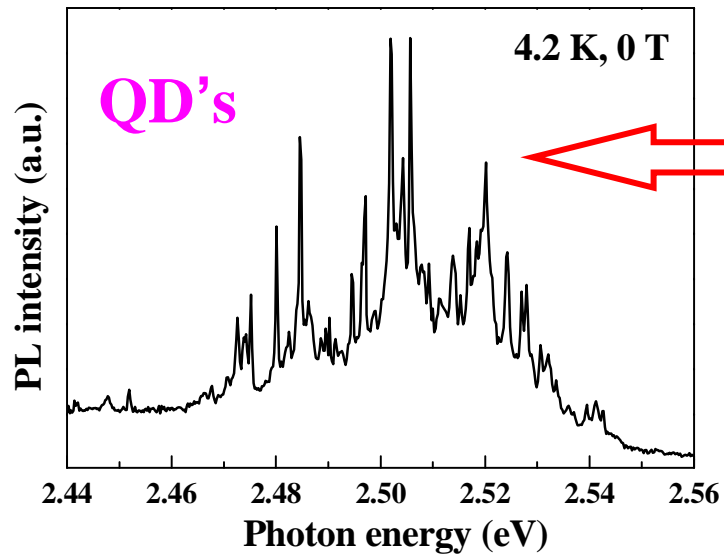


➤ Selective detection of spin-polarized excitons in the QD's, determining spin loss

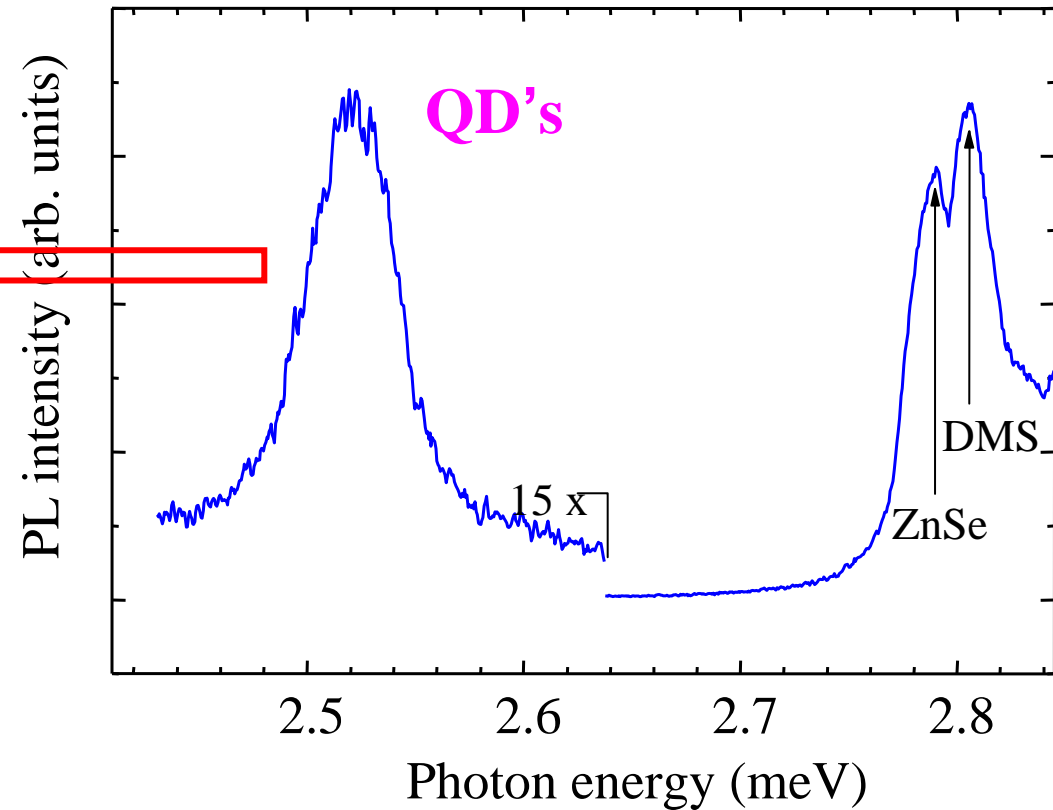
Photoluminescence

Micro-PL

(reference sample)

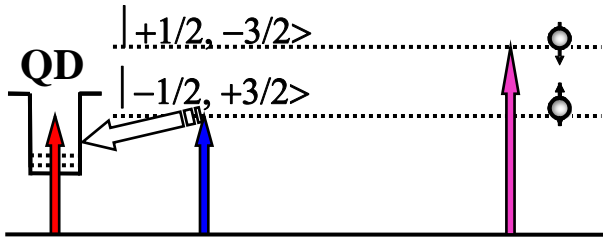


Macro-PL

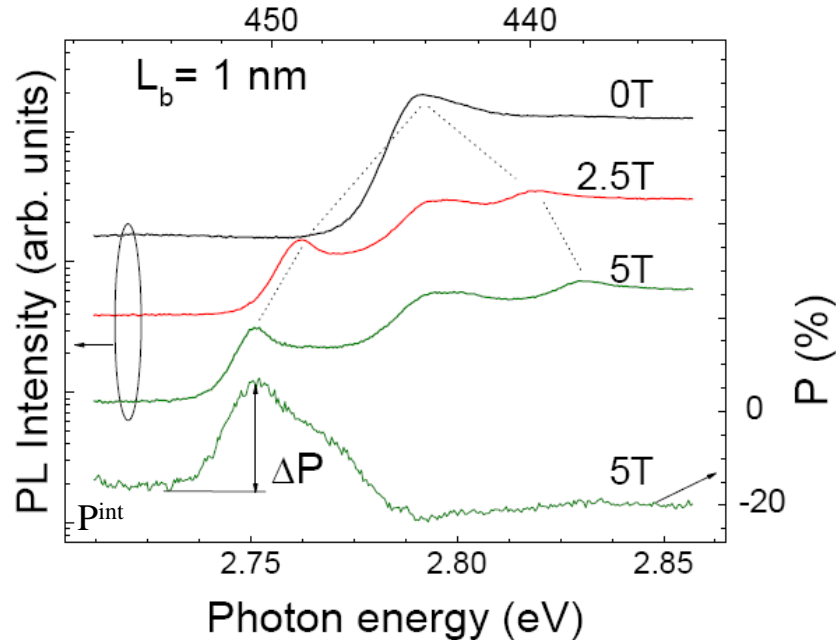


Excitation of Polarized PL

DMS, $B \neq 0$



Wavelength (nm)



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

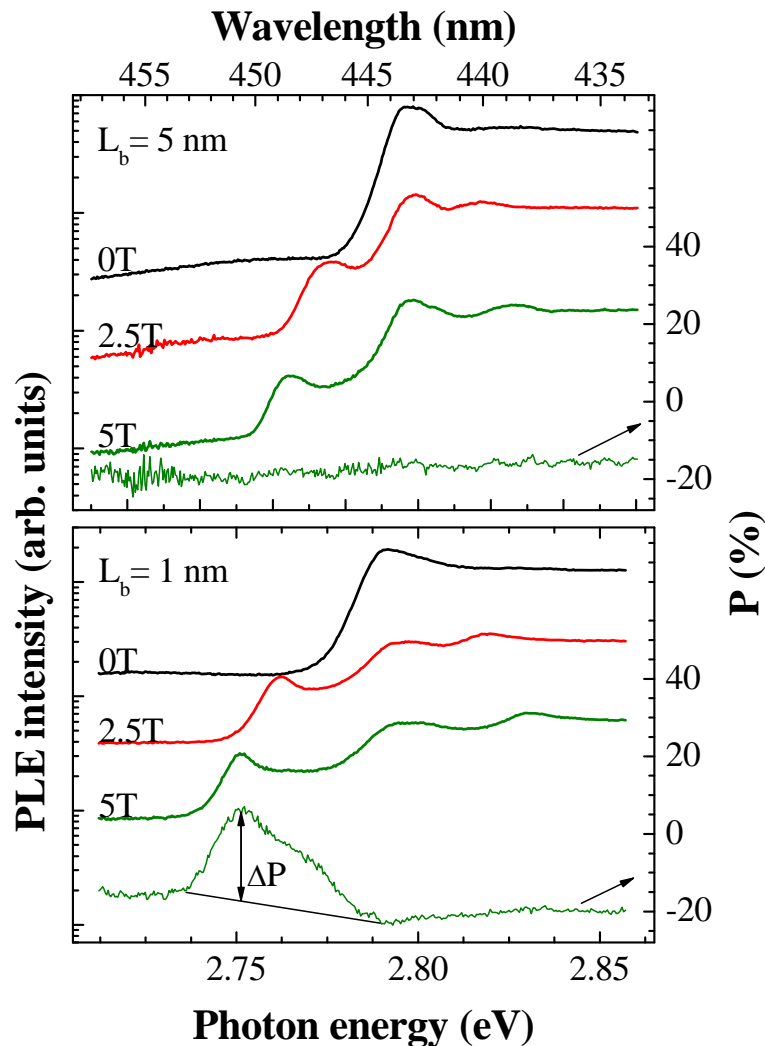
- **Below DMS excitation:**

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

- **Resonant DMS excitation:**

- $P = (\sigma^+ - \sigma^-) / (\sigma^+ + \sigma^-) \nearrow$
- $\Delta P = P - P_{int} > 0$
- **Spin injection from DMS**

Carrier and spin injection: Dependence on barrier thickness



Carrier injection from DMS:

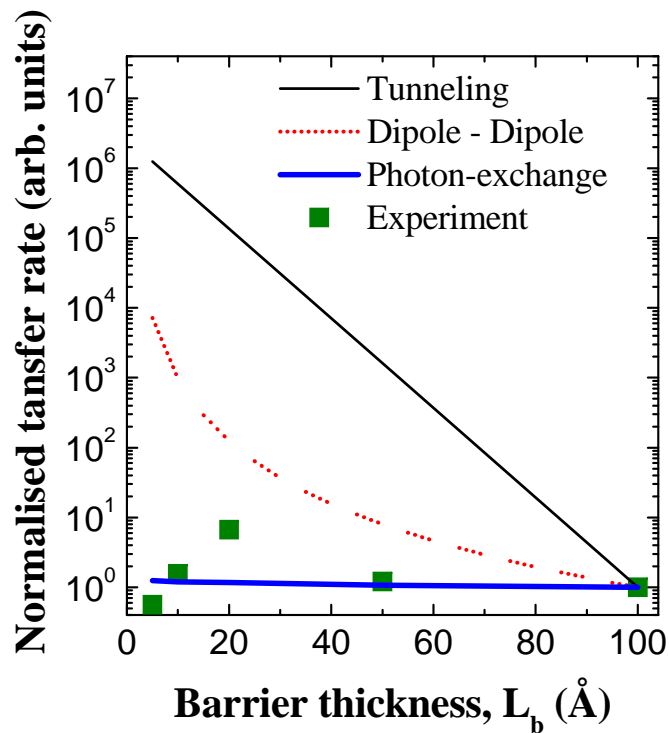
- Efficient, independent on barrier thickness L_b

Spin injection from DMS

- Strong dependence on L_b

Origin?

Carrier injection: Mechanism



Possible mechanisms for carrier injection:

✗ Tunneling:

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

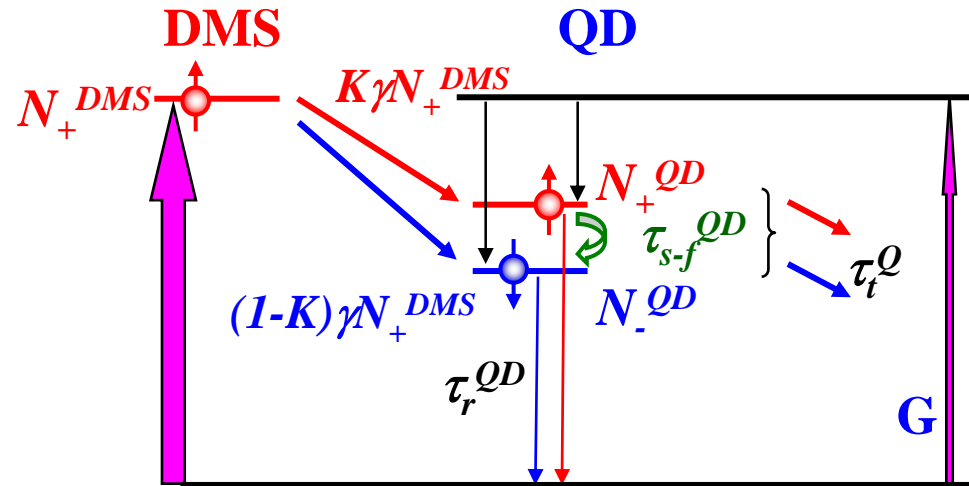
✗ Dipole-dipole interaction:

- Strong dependence on L_b , $\sim L_b^{-4}$

✓ Photon-exchange:

- Weak dependence on L_b
 - Consistent with experiment

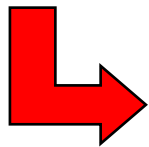
Spin Injection: Rate Equation Analysis



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

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

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

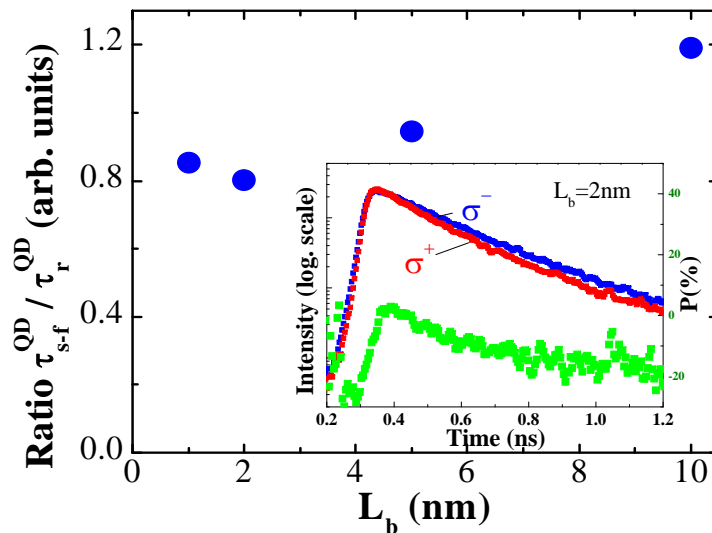


$$P = \underbrace{\frac{1 - e^{\Delta E/kT}}{1 + e^{\Delta E/kT}}}_{\text{INTRINSIC}} + \underbrace{\frac{2K - 1}{\left(1 + \frac{G}{\gamma N_+^{DMS}}\right) \left(1 + \frac{\tau_r^{QD}}{\tau_{s-f}^{QD}}\right)}}_{\text{DMS - INDUCED } = \Delta P}$$

Parameters?

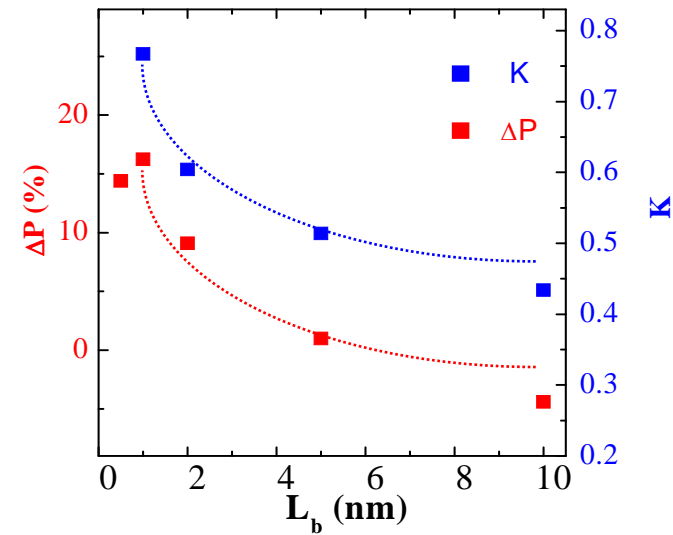
Spin Injection: Time-resolved Polarized PL

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 $\text{Zn}_{0.93}\text{Mn}_{0.07}\text{Se}$ 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