Heating Efficiency of the Mn Spin System by Photoexcited Holes in Type-II (Zn,Mn)Se/(Be,Mn)Te Quantum Wells

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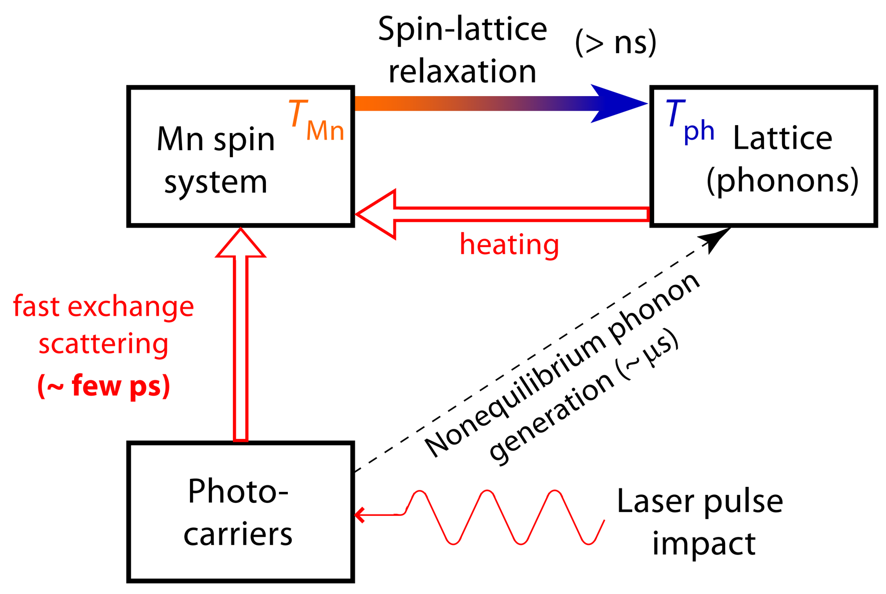
Objectives

- We study the relationship between the lifetime of hot holes and the heating efficiency of the Mn spin system in $Zn_{0.99}Mn_{0.01}Se$ layers of $Zn_{0.99}Mn_{0.01}Se/Be_{0.93}Mn_{0.07}Te$ heterostructures with type-II band alignment under different levels of optical excitation

  → The experimental findings highlight the importance of multiple hole spin-flip processes and allow us to estimate the time for spin- and energy-transfer from photogenerated holes to the Mn spin system

Introduction

- Photogenerated or electrically injected free carriers with excess kinetic energy can cause heating of the Mn spin system by converting their kinetic energy to the increase of the Mn spin temperature
- In external magnetic field which induces Zeeman splitting of the Mn spin states, exchange carrier scattering on the localized Mn spins provides simultaneous spin- and energy-transfer into the Mn spin system
- Two ways (direct and indirect) for the spin- and energy-transfer from the hot carriers to the Mn spin system are relevant in diluted-magnetic semiconductor (DMS) heterostructures [see scheme]



Simultaneous spin- and energy-transfer & type-II band alignment

- Hot carrier, even having sufficient kinetic energy, cannot exchange it with the Mn spin, if its spin is not properly oriented

  → Number of interactions for a hot carrier is controlled by ratio of carrier cooling time and carrier spin relaxation time

Electron in II-VI DMS quantum wells can typically flip only one Mn spin

For hole with its strong spin-orbit interaction and fast spin relaxation time, multiple angular momentum transfer to the Mn spin system shall be possible

(Zn,Mn)Se/(Be,Mn)Te heterostructure with type-II band alignment offers remarkable opportunity to control the hole lifetime in (Zn,Mn)Se layer either by structure parameters, i.e. thickness of (Zn,Mn)Se layer, or excitation density which controllably varies band bending

→ Potential minimum of valence band belongs to (Be,Mn)Te layer

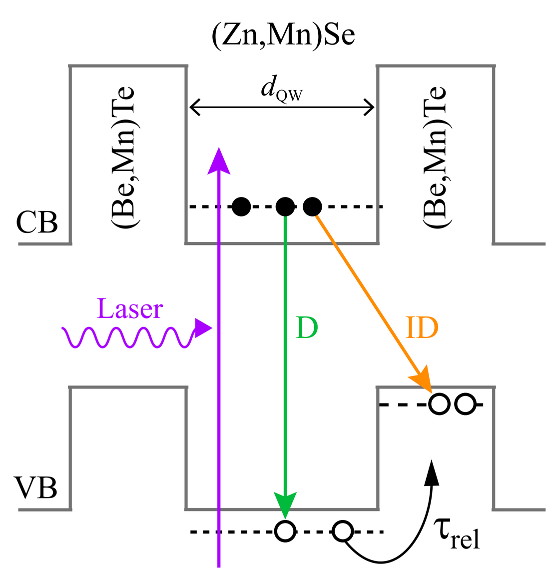
→ Hole which is photogenerated in (Zn,Mn)Se layer scatters to (Be,Mn)Te layer

This scattering time depends on above mentioned parameters and limits considerably the lifetime of hot hole in (Zn,Mn)Se layer

Characteristics of the Samples

- $Zn_{0.99}Mn_{0.01}Se/Be_{0.93}Mn_{0.07}Te$ undoped multi-QW structures with type-II band alignment and different layer thicknesses, denoted as 20/10 nm and 10/5 nm

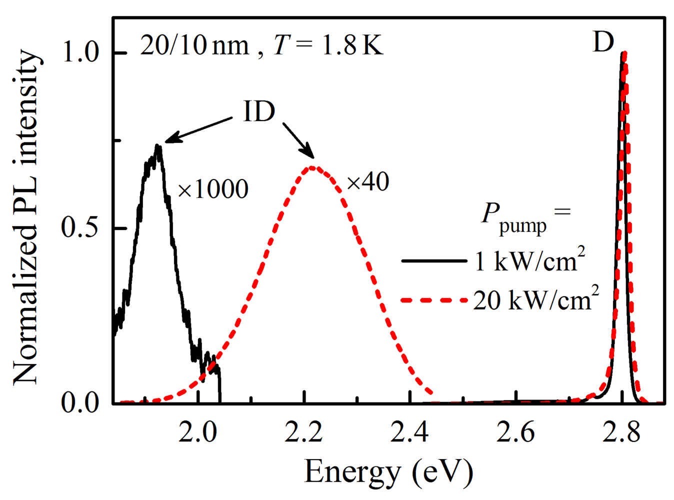
Scheme of bandstructure



- Spatial separation of electrons and holes

Much stronger localization of above-barrier hole state in sample with thicker (Zn,Mn)Se layer leads to strong τ_{rel} dependence on width of respective layer

Photoluminescence



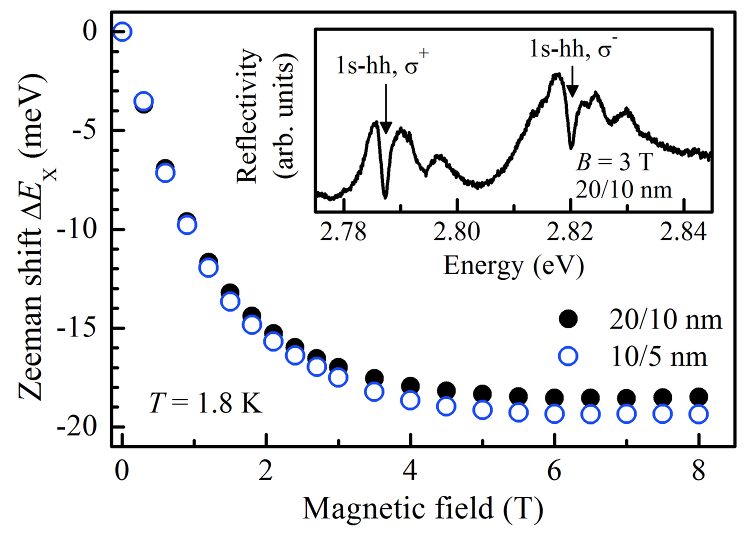
- Spectral position and shape of indirect emission line strongly depend on excitation density due to internal electric fields

  → strong band bending

  → formation of metastable above-barrier hole states

  → considerable increase in time τ_{rel} of hole relaxation process

Magneto-Reflectivity & Giant Zeeman Effect



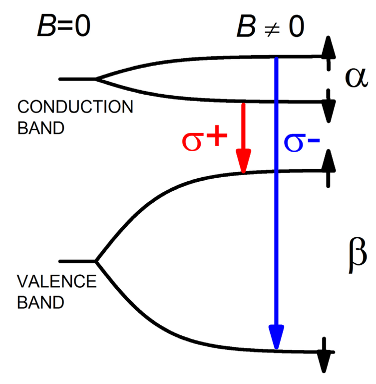
- Giant Zeeman splitting of heavy-hole exciton

$$\Delta E_z = (\delta_e\alpha - \delta_h\beta)N_0 x\langle S_z\rangle$$

- Mean thermal value of Mn spin component along magnetic field

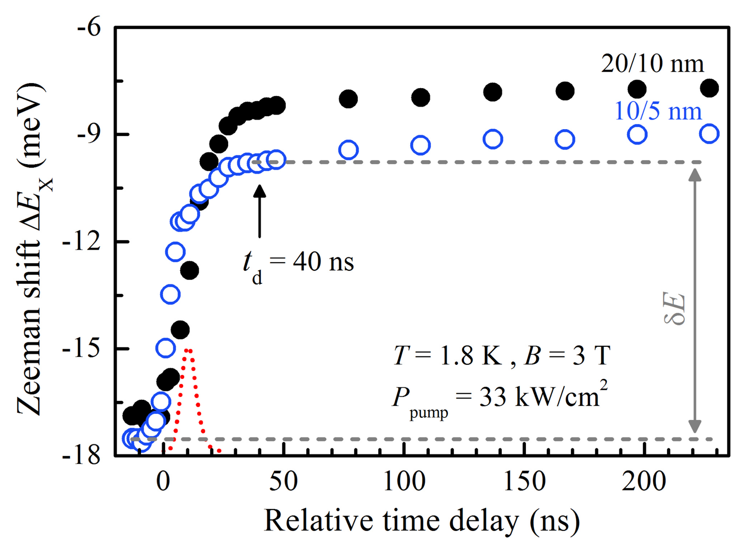
$$\langle S_z\rangle = -S_{\text{eff}}(x)\mathrm{B}_{5/2}\left[\frac{5\mu_B g_{Mn} B}{2k_B(T_{Mn}+T_0(x))}\right]$$

modified Brillouin function



- Static magnetization of (Zn,Mn)Se layers is very weakly influenced by presence of Mn ions with high concentration in adjacent (Be,Mn)Te layers

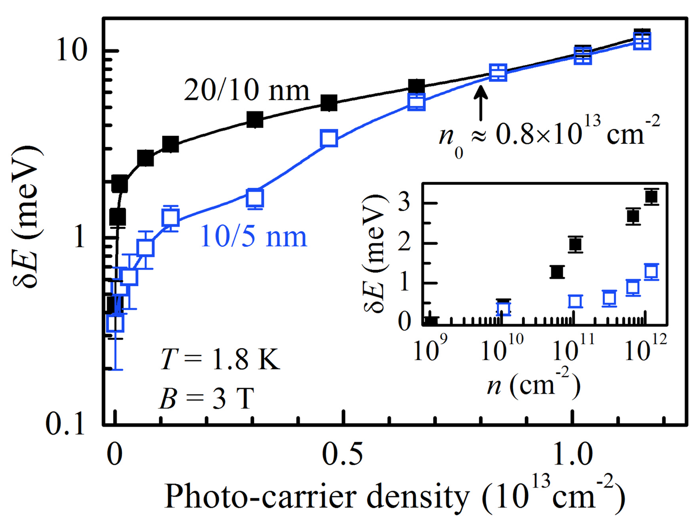
Exciton giant Zeeman shift as function of time delay relative to pump pulse



- Pump & Probe reflectivity:
  - Pulsed pump laser excites sample, incidence at ~10ns
  - Probing with emission from dye-liquid *Coumarin* generated by second pulsed laser
- Giant Zeeman shift is reduced mainly during pump laser pulse, i.e. during presence of hot photogenerated carriers in $Zn_{0.99}Mn_{0.01}Se$
- For t_d > 40 ns: ΔE_X does not change considerably thus indicating the presence of a heated Mn system with almost constant spin temperature of T_{Mn} = 9 K

Efficiency of Mn-Spin System Heating by Photo-Holes

Photo-carrier-density dependence of δE averaged over time interval 40 - 230 ns



- For 10^{10} cm^{-2} < n < 8 x 10^{12} cm^{-2}: δE in 20/10 nm sample exceeds that of 10/5 nm sample by a few meV

  → Mn heating efficiency is stronger in sample with thicker $Zn_{0.99}Mn_{0.01}Se$ layers

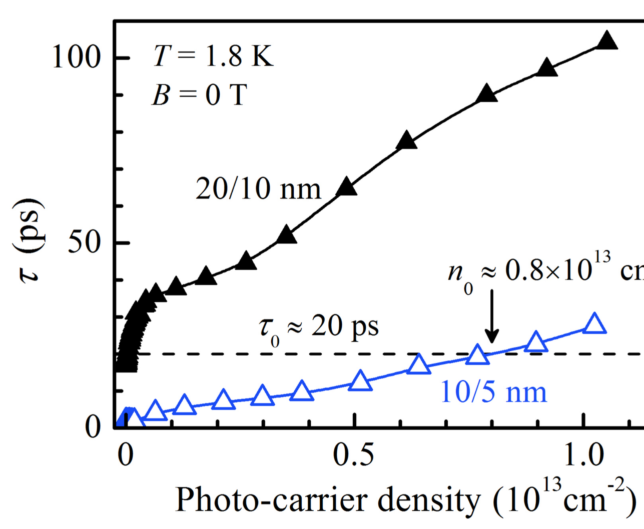
Different heating efficiencies found for various carrier concentrations cannot be explained by electron heating

(i) Concentration of electrons confined in (Zn,Mn)Se layers is the same in both structures and is limited by recombination only

(ii) Each electron can provide only one exchange scattering with a Mn ion

Different heating efficiencies are related to Mn heating by hot holes

Lifetime of photo-holes in (Zn,Mn)Se layers dependent on photo-carrier density



- Due to longer lifetime of hot holes in 20-nm-thick (Zn,Mn)Se layers, the holes on average contribute stronger to Mn heating
- At high carrier densities ($n \geq n_0$), the hole lifetime in 20-nm-thick layers is still much longer than that in the 10-nm-thick layers, but heating efficiency is similar
- At n_0 the lifetime of holes in 10/5 nm sample reaches ~20 ps

  → This time is sufficient for complete relaxation of holes reaching a spin temperature below Mn spin temperature

Characteristic time for spin- and energy-transfer from photoexcited holes to Mn spin system in $Zn_{0.99}Mn_{0.01}Se$ DMS can be estimated to 20 ps

Time of 20 ps is long compared to time of exchange scattering between photo-holes and spins of Mn ions → Each hole undergoes multiple scatterings with Mn ions

- Initial and final states of hole belong to same spin subband
- Due to strong spin-orbit interaction, any momentum scattering of a hole changes its spin state as well, thus enabling multiple spin-flip transitions in Mn ions

Conclusion

- Efficiency of spin- and energy-transfer depends on hole lifetime in (Zn,Mn)Se layer

  → Multiple spin-flip scattering of a hole with localized spins of Mn^{2+} ions
- Hole lifetime, limited by scattering into (Be,Mn)Te, strongly depends on excitation power and layer thickness
- Characteristic time for spin- and energy-transfer in DMS with 1% Mn concentration estimated to 20 ps