Spin-Flip Raman Scattering of Electron and Heavy-Hole in CdTe/(Cd,Mg)Te Quantum Well Enabled by Anisotropic Exchange

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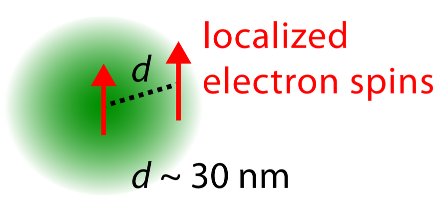
MSS 2013, Wroclaw

Introduction

- For spintronic and quantum information applications, understanding of fundamental interactions between confined carrier spins is essential
  - → These interactions may limit information handling due to spin relaxation



- Isotropic and anisotropic magneto-dipole & **exchange coupling**

  10^{-9} meV ≪ **0.1 meV**

  *[e.g., O. Gywat et al., PRB **73**, 125336 (2006)]*

- Study of electron-hole exchange as well as exchange between identically charged carriers
- Exchange-related spin relaxation has been studied mostly for donor-bound electrons

The effect of anisotropic exchange interaction between an exciton and a resident electron or hole localized by potential fluctuations in a quantum well (QW) has not been addressed in detail yet

- Resonant spin-flip Raman scattering (SFRS) offers advanced possibilities to study carrier spins
  - → While the exciton-SFRS is arranged via simultaneous spin-flips of the constituents electron and hole, single carrier spin-flip of electron or hole violates the conservation of angular momentum in high-symmetry, low-dimensional structures

Possible mechanisms due to which the resonant Raman spin-flip of electron or hole can nevertheless take place have not been discussed yet

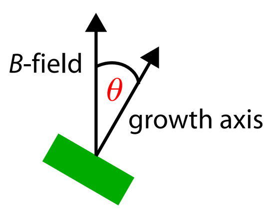
Objectives

Anisotropic exchange

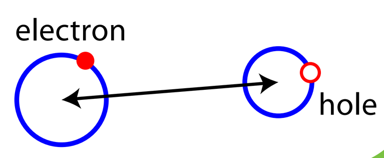
→ Resonant Raman scattering of carrier spins in excitons

Influence of mixing of states

Geometry of experiment: angle dependence

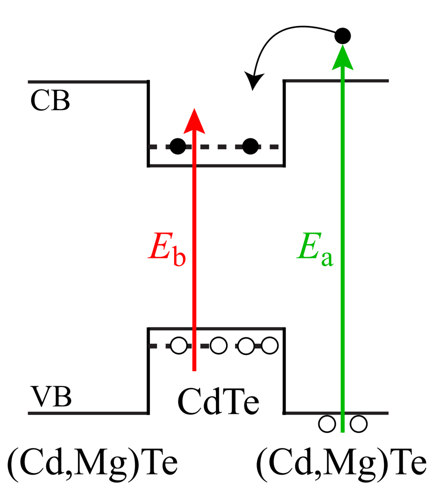


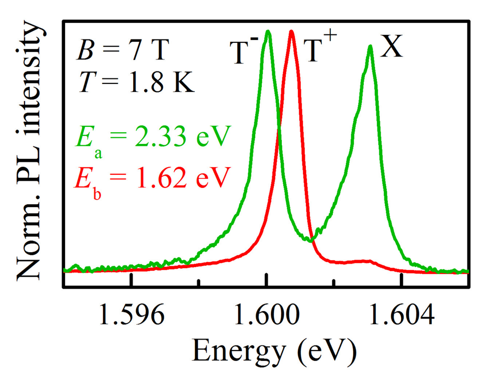
How important is reduction of exciton symmetry ?

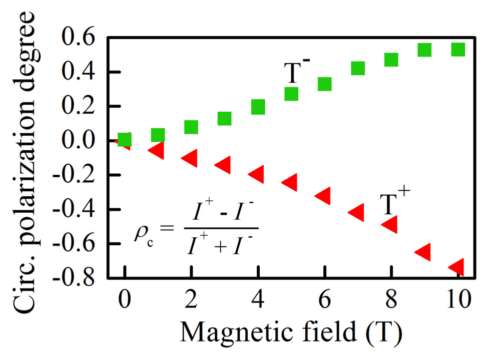


The Sample

$CdTe/Cd_{0.63}Mg_{0.37}Te$ quantum well







$|-3/2,+3/2,+1/2\rangle \longrightarrow |+3/2\rangle$: σ^-
Positive trions T^+ → QW is p-doped
Actually: coexistence of resident holes ($10^{10}/cm^2$) and electrons ($10^9/cm^2$)

$|+3/2,+1/2,-1/2\rangle \longrightarrow |+1/2\rangle$: σ^+
Negative trions → QW is n-doped

*[G. Bartsch et al., PRB **83**, 235317 (2011)]*

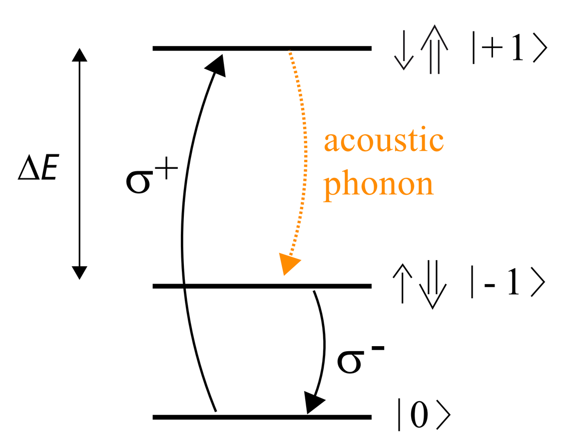
- As the charge state of the exciton is tunable by additional above-barrier illumination, both positive and negative trions can be studied in the same sample

Theory: Spin-Flip Scattering of Exciton

Selection rules: In electric-dipole-approximation & backscattering configuration

- Total change of photon angular momentum: $\Delta L = 0$ or ± 2

Faraday geometry (B||z), neutral exciton

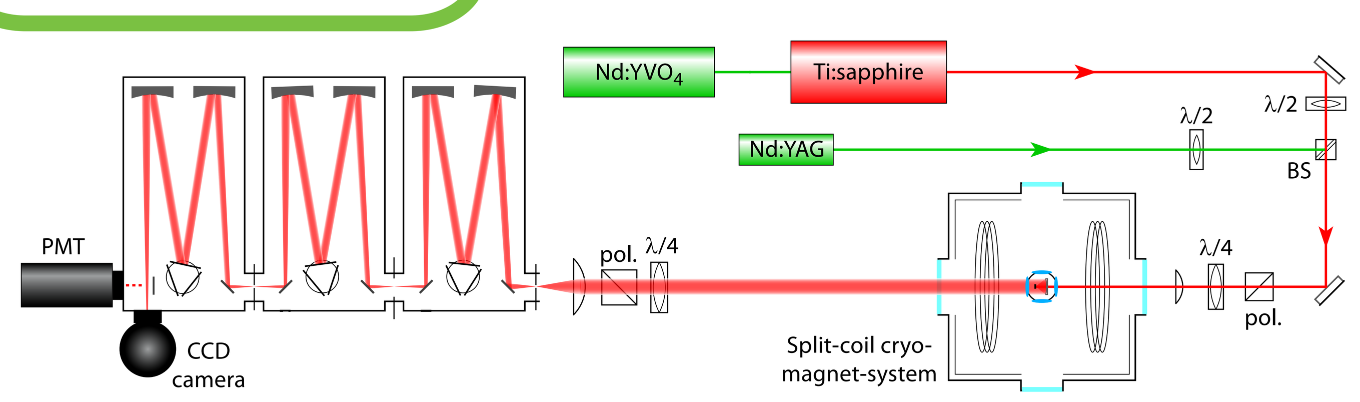


- SFRS of exciton allowed ...
  - ... in crossed circular polarizations
  - ... only as third-order process

Single spin-flip of electron or heavy-hole is not allowed !!

- Raman shift:
  → $\Delta E = g\,\mu_B\,B$ — The shift of spin-flip Raman line is proportional to exciton g factor

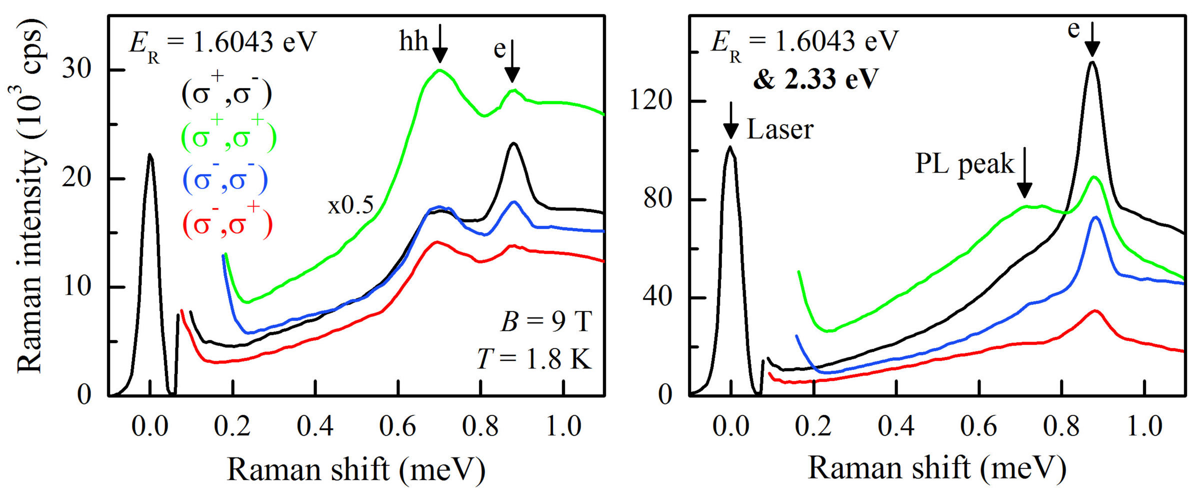
Experimental Setup



Anisotropic Exchange Interactions in Exciton

Observation of single spin-flips of electron and heavy-hole

Circularly polarized Raman spectra for resonant excitation of exciton in Faraday geometry (**B** || **z** , $\theta = 0°$):



SFRS intensity ratios:

	σ^+,σ^-	σ^+,σ^+	σ^-,σ^-	σ^-,σ^+
e-SFRS	1	0.31	0.39	0.15
hh-SFRS	0.27	1	0.33	0.28

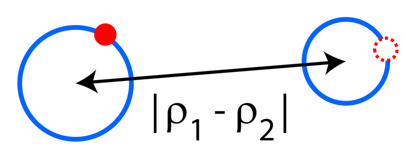
Above-barrier illumination ...

- ... suppresses the hh-SFRS
  - → **hh spin-flip mechanism involves resident hole**
- ... enhances the e-SFRS intensity but does **not** change the intensity ratios !!
  - → **el. spin-flip mechanism includes neutral exciton**

What are the spin-flip mechanisms ?

Anisotropic flip-stop-like exchange interaction

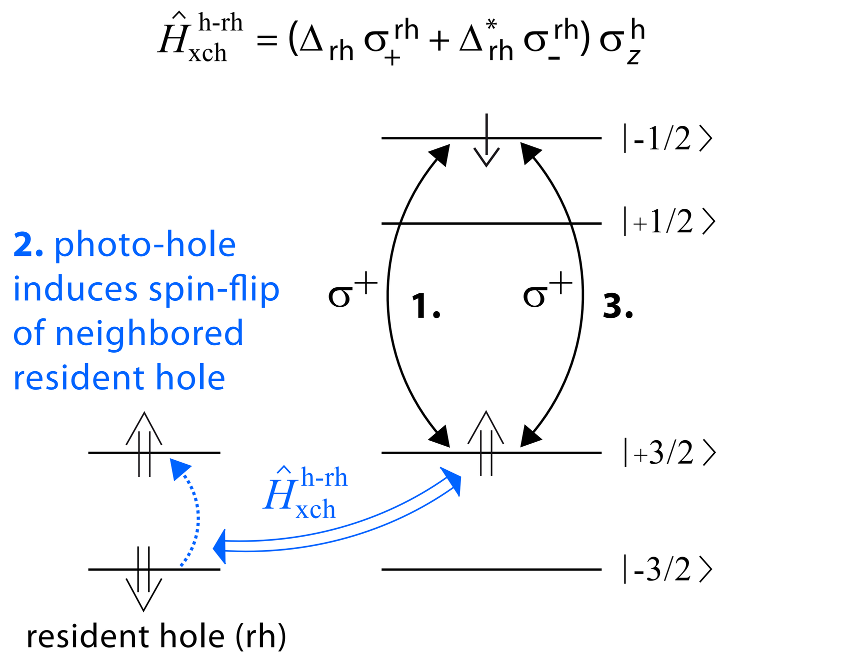
- → changes one carrier spin while leaving the other spin invariant
- → results from reduced symmetry of exciton complex, in-plane localization centers ρ of two carriers are spatially shifted



*[E. L. Ivchenko, Sov. Phys. Solid State **34**, 254 (1992)]*

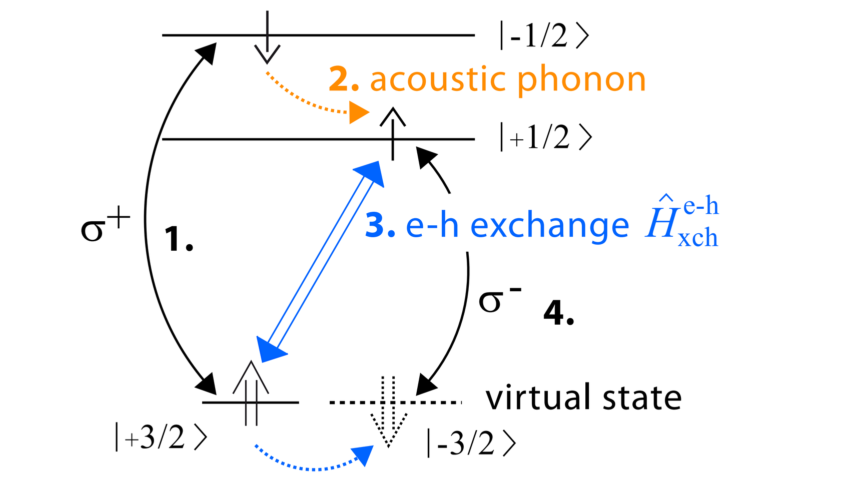
Heavy-hole spin-flip

$$\hat{H}^{h\text{-}rh}_{xch} = (\Delta_{rh}\,\sigma^{rh}_+ + \Delta^*_{rh}\,\sigma^{rh}_-)\,\sigma^h_z$$



Electron spin-flip

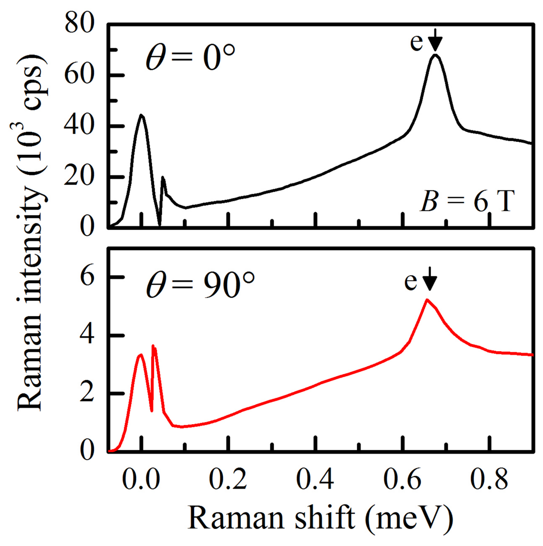
$$\hat{H}^{e\text{-}h}_{xch} = (\Delta_h\,\sigma^h_+ + \Delta^*_h\,\sigma^h_-)\,\sigma^e_z$$



Raman shift determined by electron Zeeman splitting

Further Properties of Single Spin-Flips

Angle-dependent attenuation of anisotropic e-hh exchange



Probability for anisotropic e-hh exchange interaction:

$$p_{xch} \sim \hbar^2/(\mu_B B)^2 \, \frac{J^2_{xch}}{(\omega_e - \omega_{hh})^2 + \Gamma^2}$$

At larger tilting angles θ the heavy-hole Larmor frequency (*g* factor) considerably deviates from the isotropic one of the electron

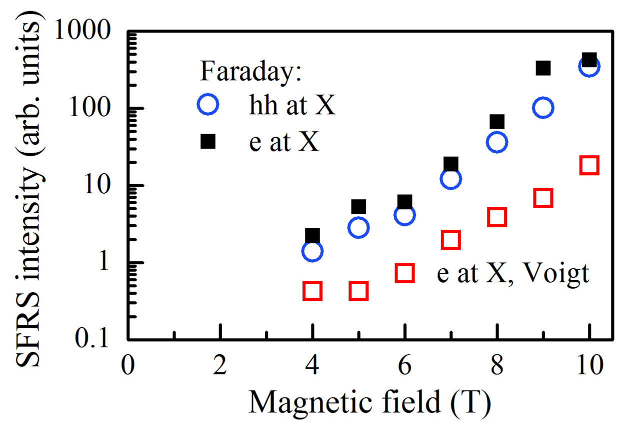
⇒ Reduction in SFRS intensity, although one would expect an increase due to stronger mixing of states

Dependence on magnetic localization

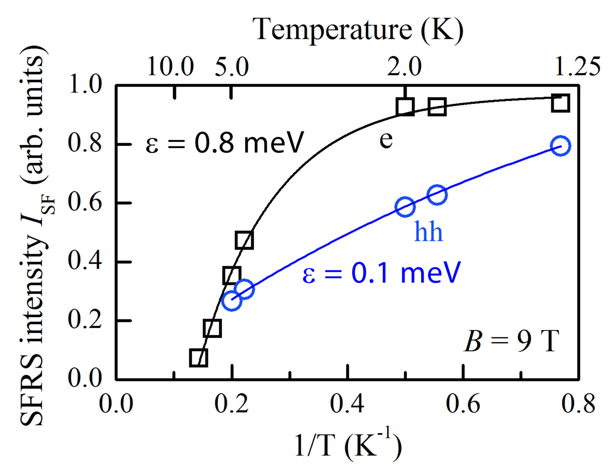
Strong shrinkage of exciton wave function in longitudinal fields

- → enhanced exciton localization & larger oscillator strength
- → longer exciton lifetime & longer spin dephasing

Enhancement of spin-flip Raman scattering intensity



Temperature-induced exciton delocalization



$$I_{SF} = I_0\left[1 - \exp\left(-\frac{\epsilon}{k_B T}\right)\right]$$

ε : deactivation energy of SFRS process

- Deactivation energy corresponds to localization energy of exciton complex
  - → For delocalized exciton complex: SFRS disappears

Conclusion

- Flip-stop anisotropic exchange as mechanism for single carrier spin-flips in exciton — Exciton symmetry must be reduced
- Tilting of magnetic field influences spin-flip Raman scattering
- Spin-flip Raman scattering further affected by:
  - polarized excitation
  - additional illumination
  - localization degree of exciton complex

*Phys. Rev. B **87**, 205316 (2013)*