Optical control of Mn spin in GaAs

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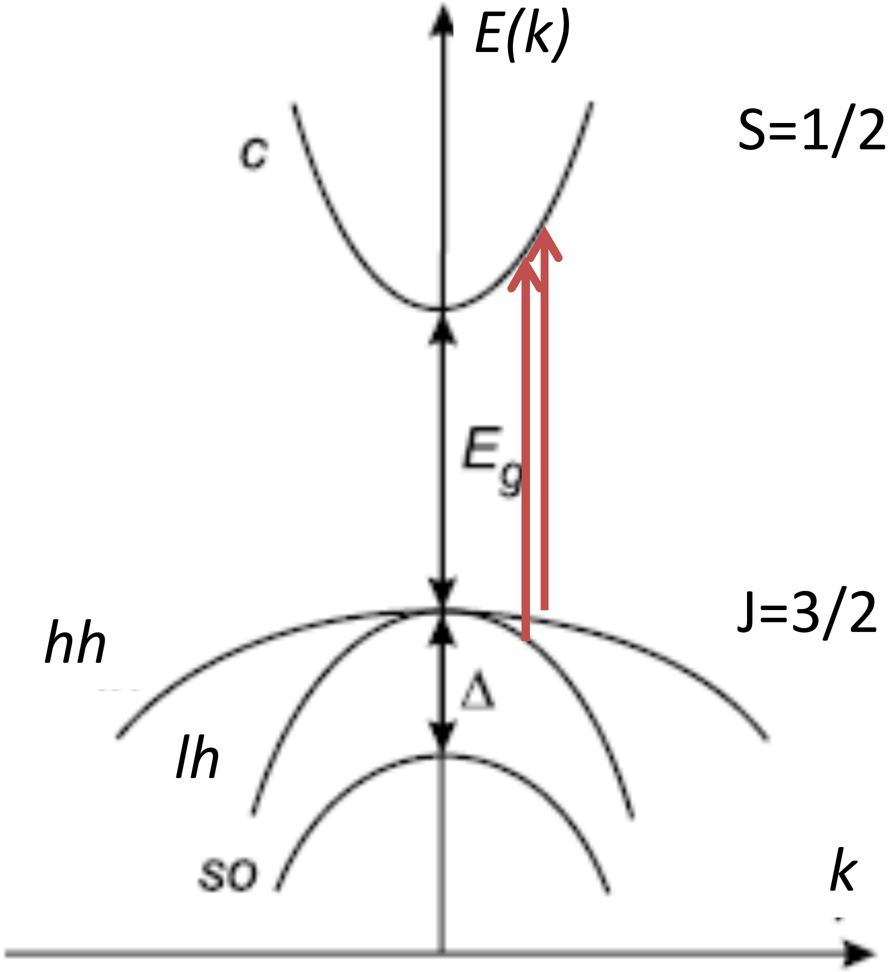
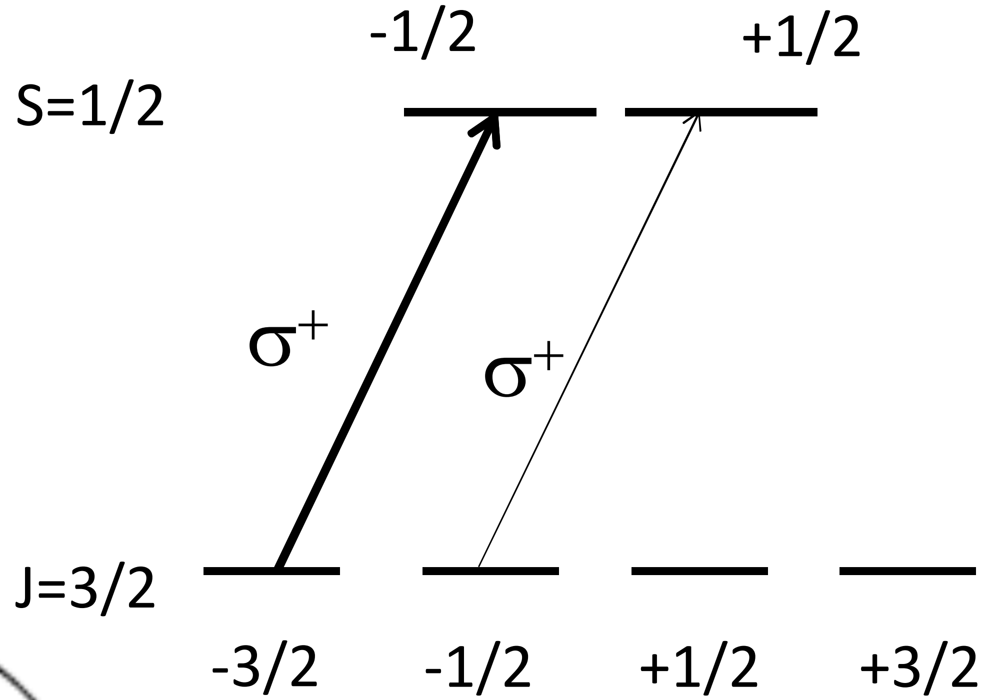
Outline

- Spin polarized electrons + Magnetic ions (Mn)
- GaAs doped with low Mn concentration (10^{18} cm^{-3})
  - Energy structure, sp-d exchange interaction
  - How to detect Mn orientation?
  - How to distinguish between A^0 and A^- ?
- Experimental results
  - Spin-flip Raman scattering (SFRS)
  - Time-resolved photoluminescence (TRPL)
- Summary

Optical orientation in GaAs





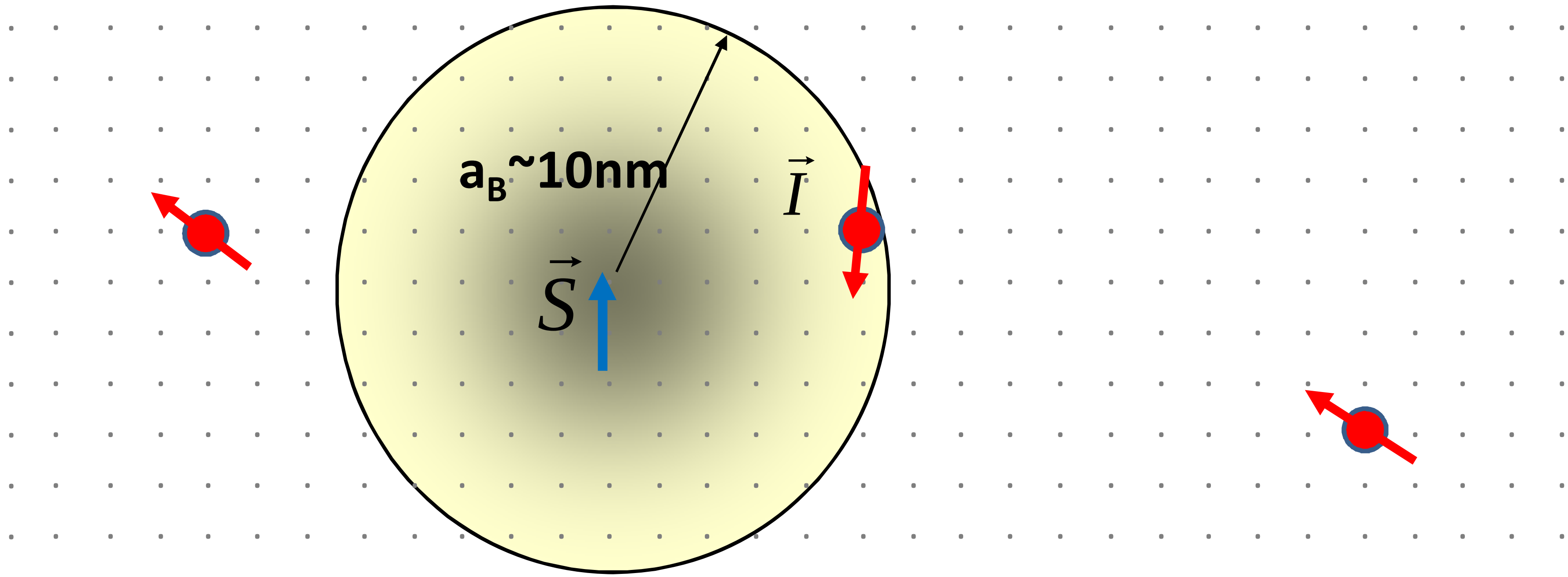
$$\rho = S_z = \frac{\tau}{\tau+\tau_S} S_{z0}$$

$$S_{z0} = 0.25$$

Spin polarized electrons + Magnetic ions

s-d exchange interaction between electron in conduction band with spin $\vec{S}$ magnetic impurity with spin $\vec{I}$.

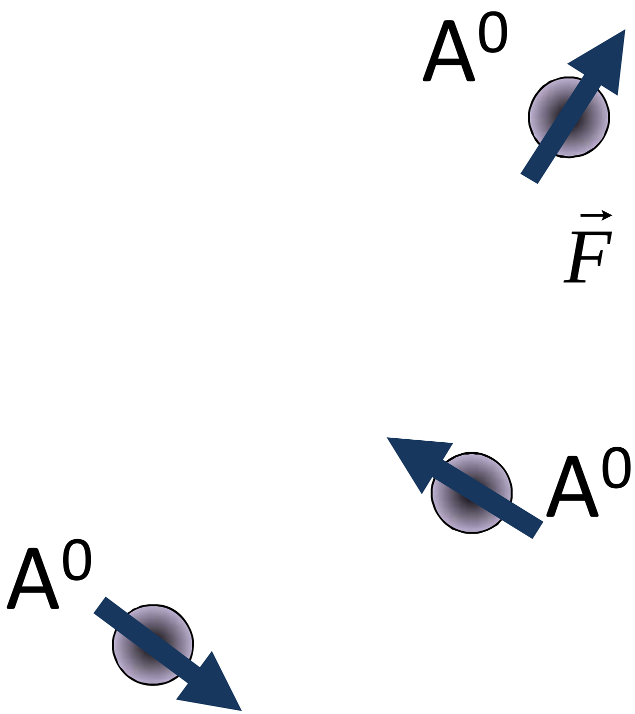
$$\hat{H}^{e-Mn}_{s-d} = -b(\hat{\vec{S}} \cdot \hat{\vec{I}})$$



GaAs doped with low Mn concentration

Mn $3d^5 4s^2 \Rightarrow$ acceptor with $a_{B,A} \approx 1$ nm, $E_A \approx 110$ meV

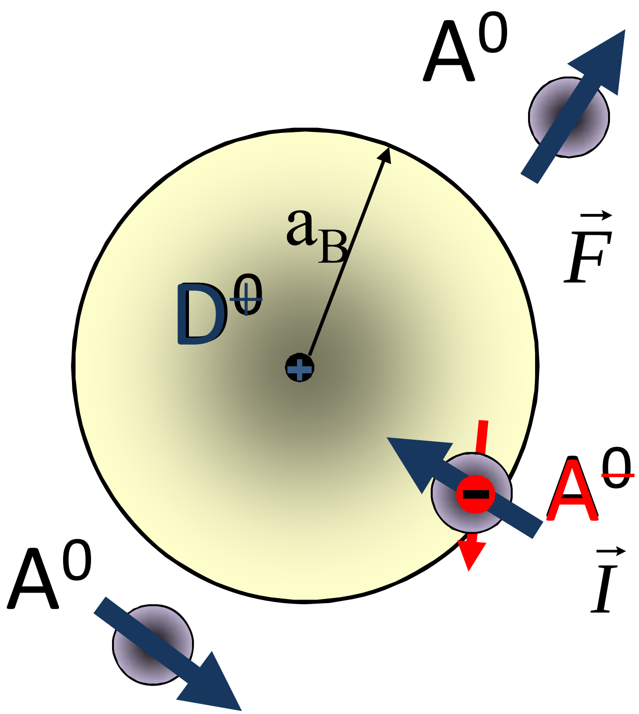
$N_A \sim 10^{17}$-10^{18} cm^{-3}



GaAs doped with low Mn concentration

$N_A \sim 10^{17}$-10^{18} cm^{-3}

Compensation with donors $N_D \sim 10^{16}$ cm^{-3} ($a_B \approx 12$ nm)



A^0 - $F = 1$

A^- - $I = 5/2$

GaAs doped with low Mn concentration

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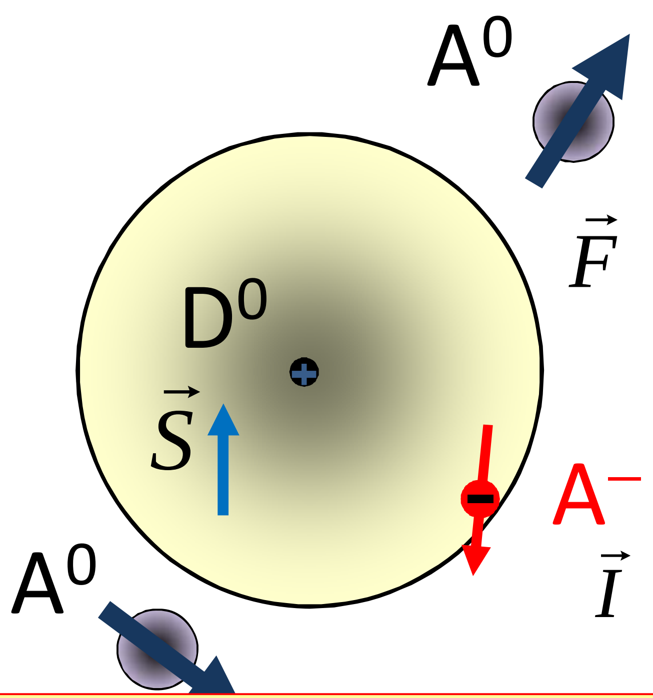


A^0 - $F = 1$

A^- - $I = 5/2$

Photoexcited electron with spin S localized on a residual donor

$$\hat{H}^{e-A^-}_{s-d} = -b(\hat{\vec{S}} \cdot \hat{\vec{I}})$$

$$\hat{H}^{e-A^0}_{exch} = -a_F(\hat{\vec{S}} \cdot \hat{\vec{F}})$$

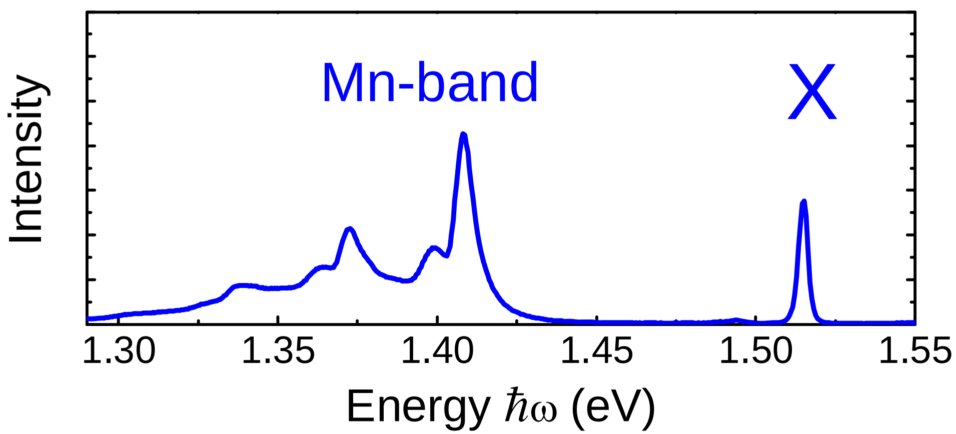
Optical orientation of electrons **+**

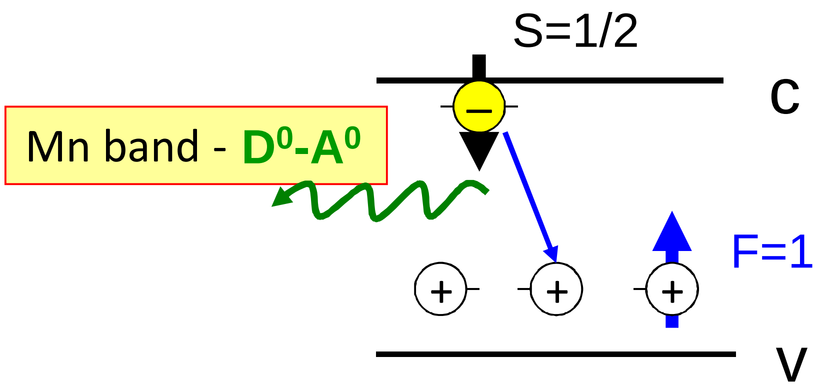
+ exchange interaction with neutral (A^0) or ionized (A^-) Mn acceptors.

How to detect Mn spin polarization?

Photoluminescence

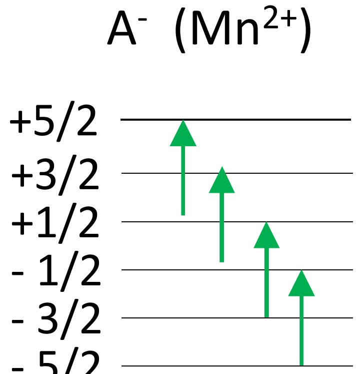
PL spectrum for $N_{Mn} = 6\times10^{17}cm^{-3}$, T = 8 K

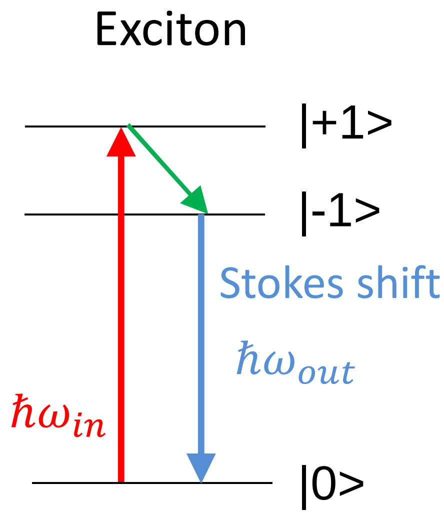




Spin-flip Raman scattering

B>0





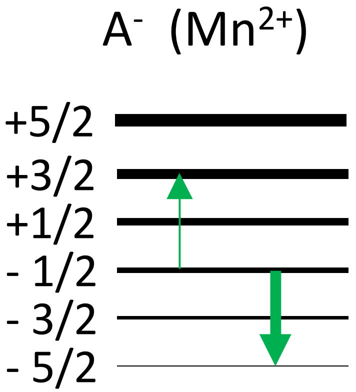
IN: $\hbar\omega_{in}$, σ^{+}

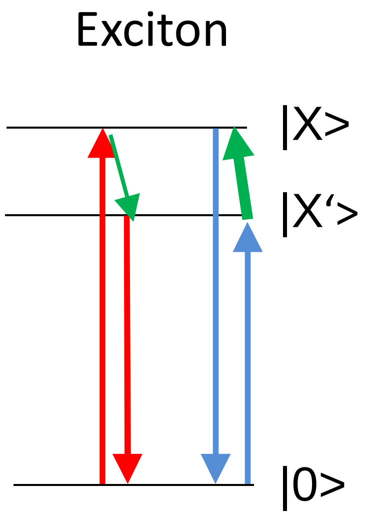
OUT: $\hbar\omega_{out}$, σ□

Balance: $\delta E = n\, \mu_B\, g_{Mn}\, B$

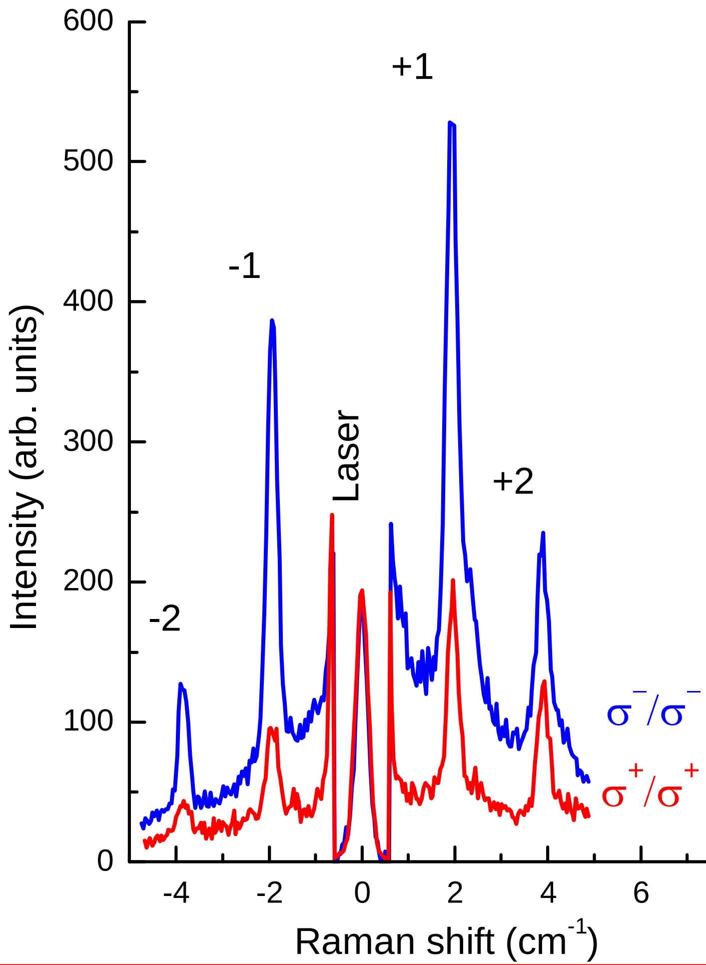
$\delta n = 2$

Spin-flip Raman scattering





Balance: $\delta E = n\,\mu_B\, g_{Mn}\, B$

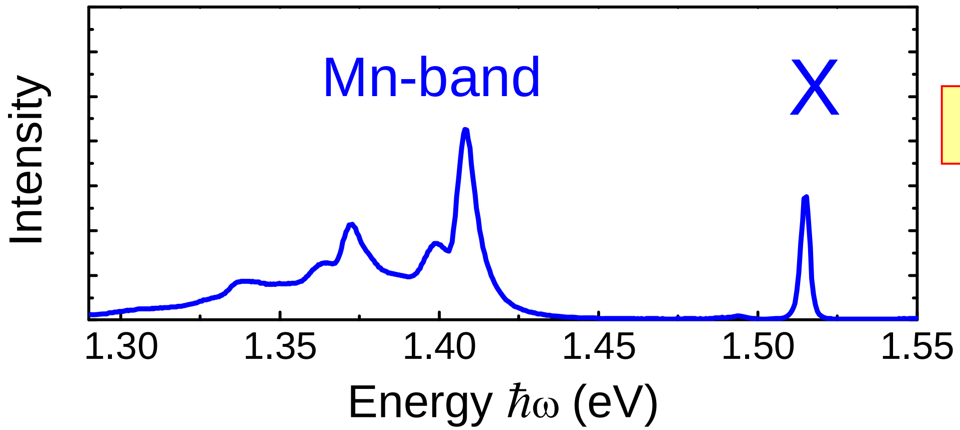


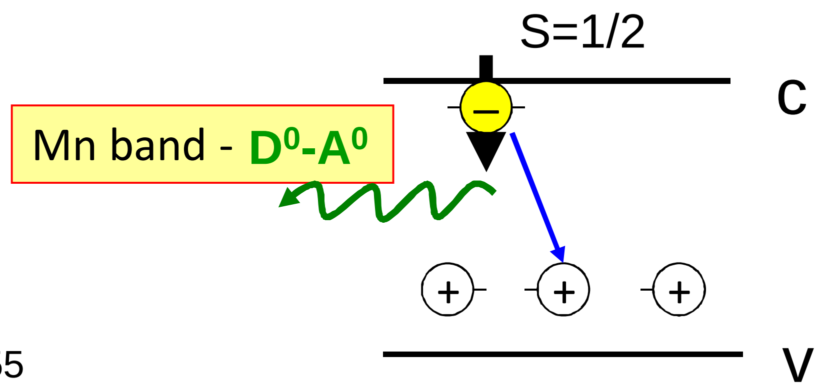
$$\eta_n^\sigma = \frac{I_{n\sigma}^S - I_{n\sigma}^{AS}}{I_{n\sigma}^S + I_{n\sigma}^{AS}} = -\frac{3n}{2(I+1)} P_M(\sigma, B)$$

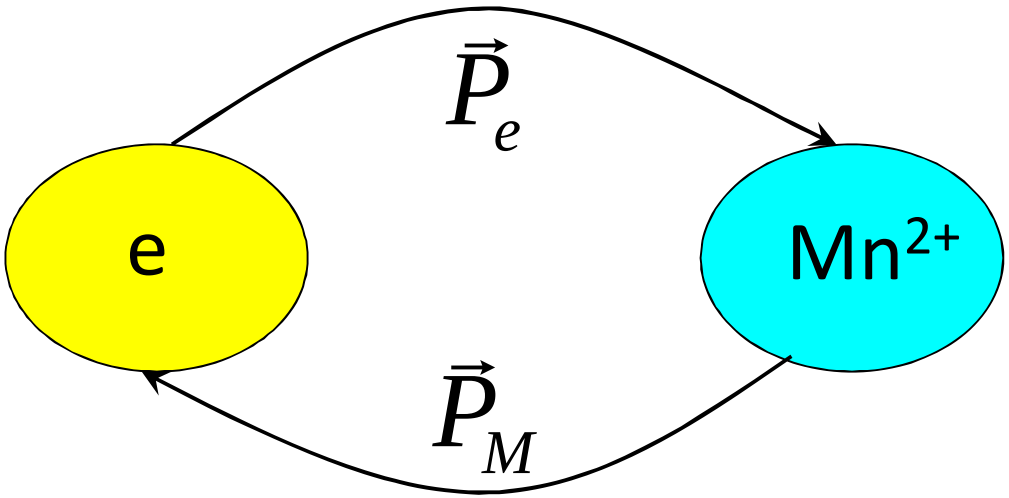
1. Distinguish between the spin flip on neutral and ionized Mn acceptors.
2. Direct evaluation of Mn polarization.

What can we find from PL?

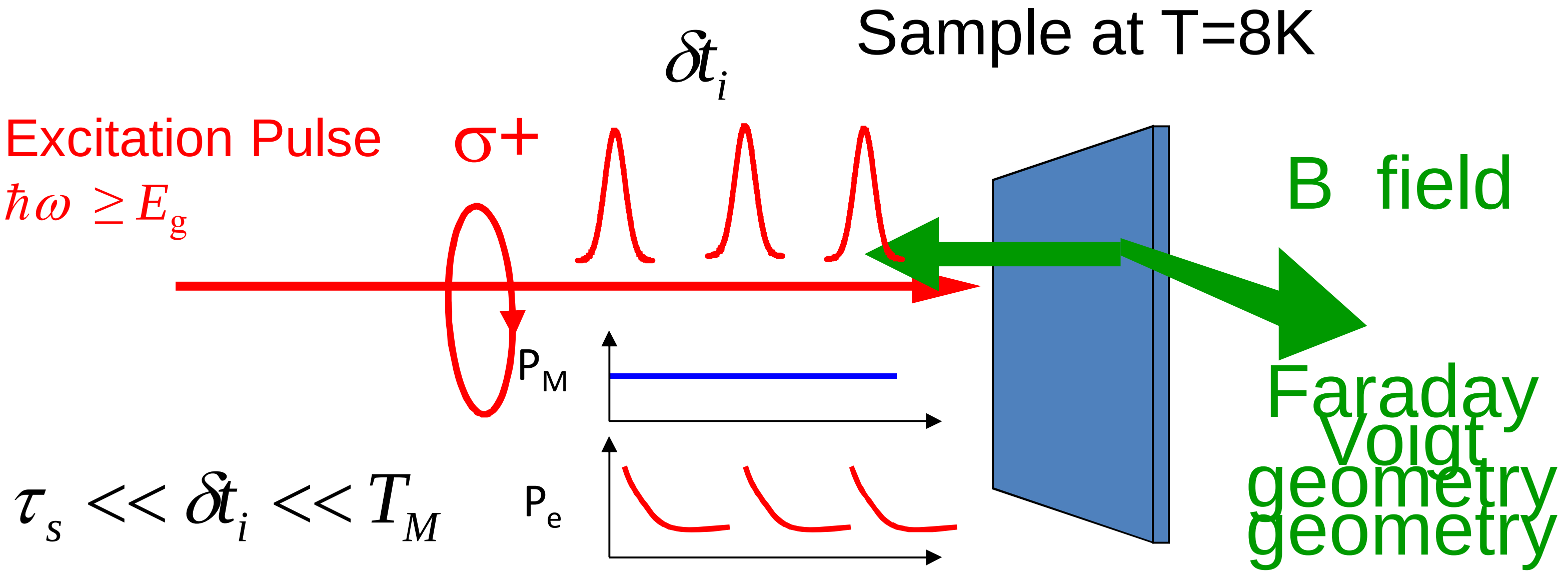
PL spectrum for $N_{Mn} = 6\times10^{17} cm^{-3}$, T = 8 K







Time- and polarization- resolved PL

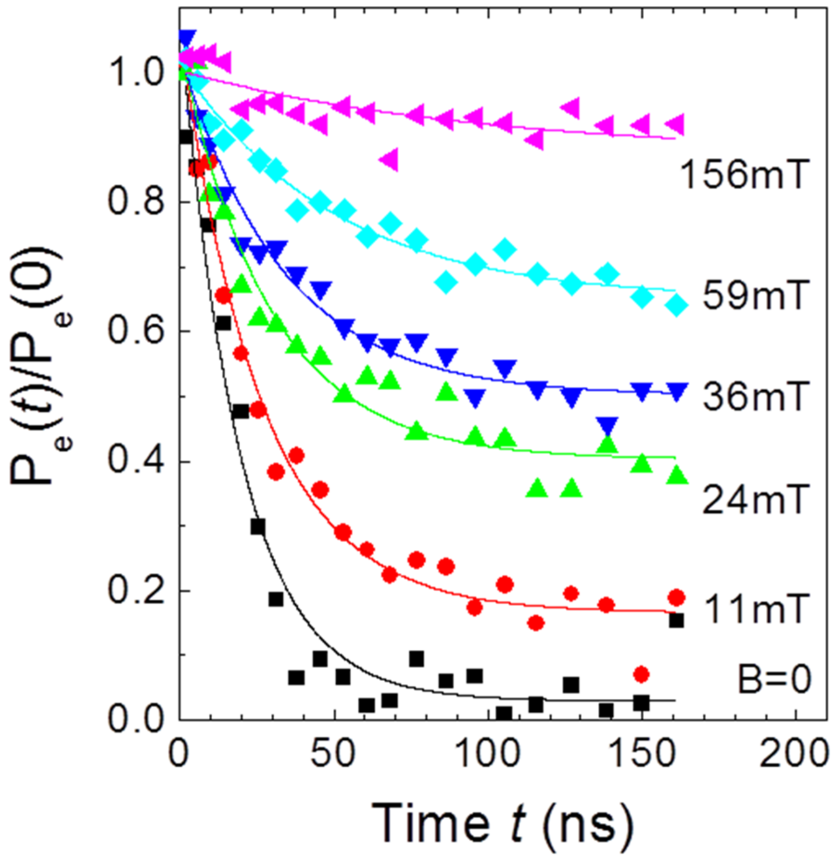


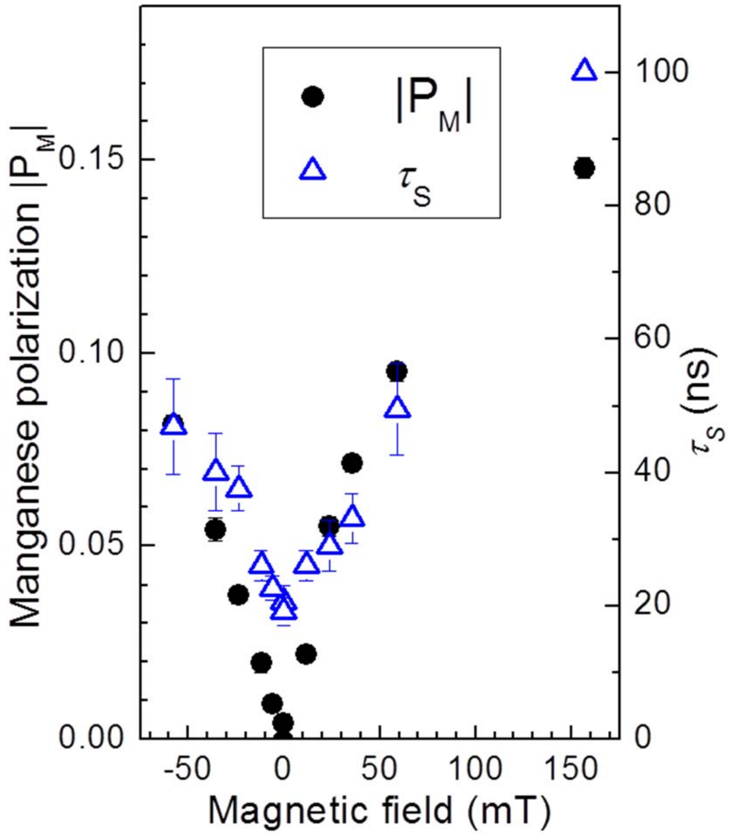
-Polarization optics selects σ+ or σ- signal
-Spectrometer filters out D^0 - A^0 transition
-Streak Camera provides time resolution < 50ps

$$I = I_+ + I_- , \qquad \rho_c = \frac{I_+ - I_-}{I_+ + I_-}$$

1. Total intensity $\quad I(t) = I(0)e^{-t/\tau} \quad$ population decay
2. Circular polarization $\quad \rho_c(t) = \rho_c(0)e^{-t/\tau_s} \quad$ spin decay

TRPL in Faraday geometry



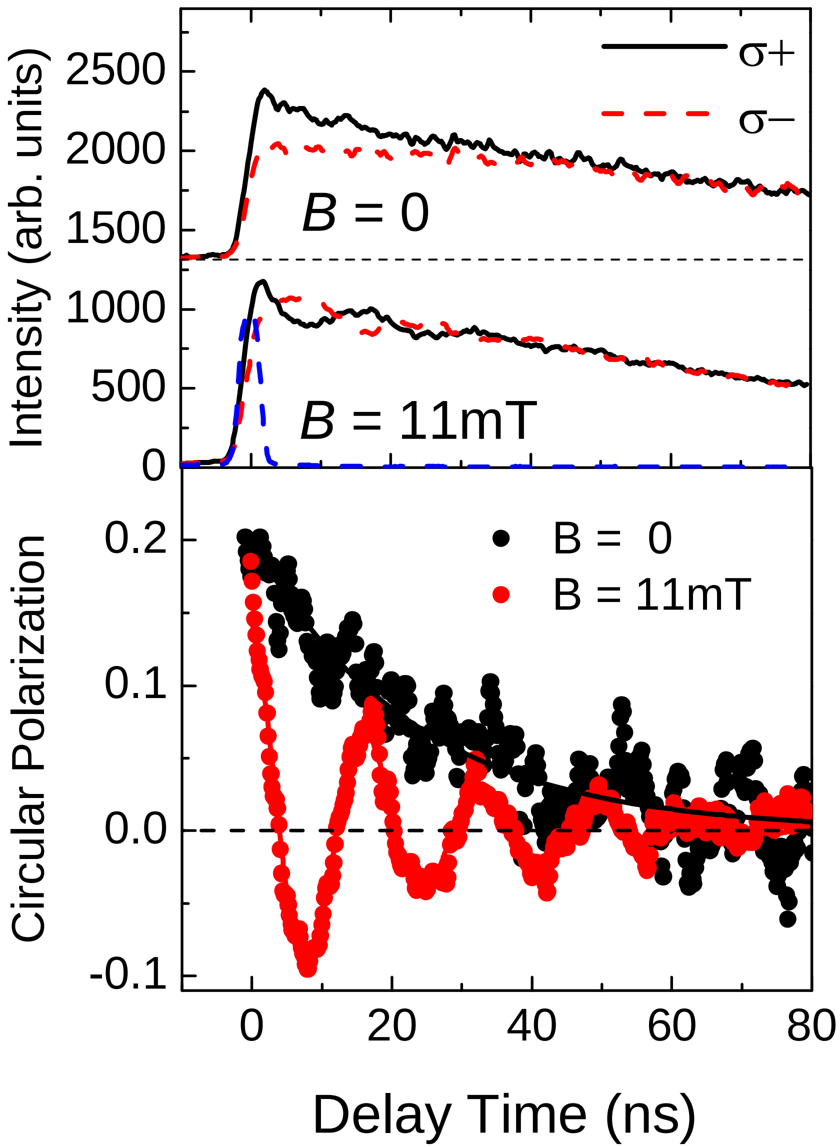


$$P_e(t) = \frac{I+1}{S+1} P_M + \left[P_i - \frac{I+1}{S+1} P_M \right] \exp\left(-\frac{t}{\tau_S} \right)$$

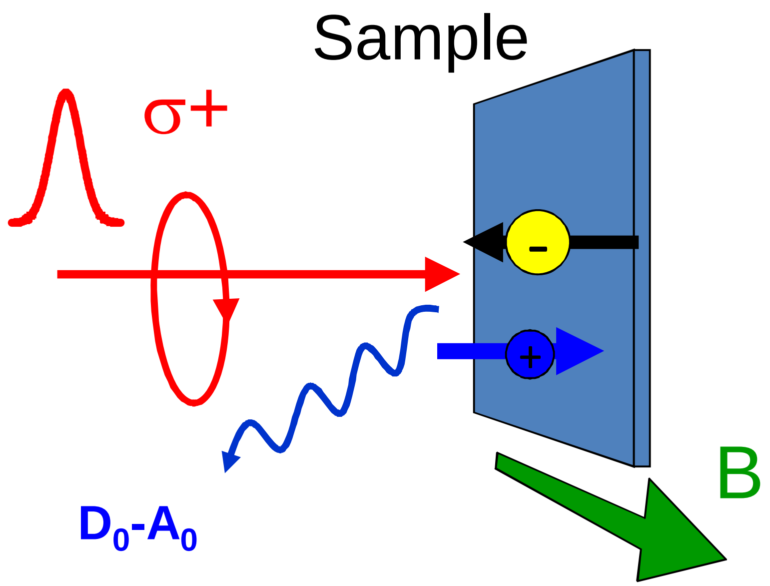
Plateau changes sign with excitation helicity
Saturation at magnetic field ~ 150 mT

→ Mn orientation

TRPL in Voigt geometry



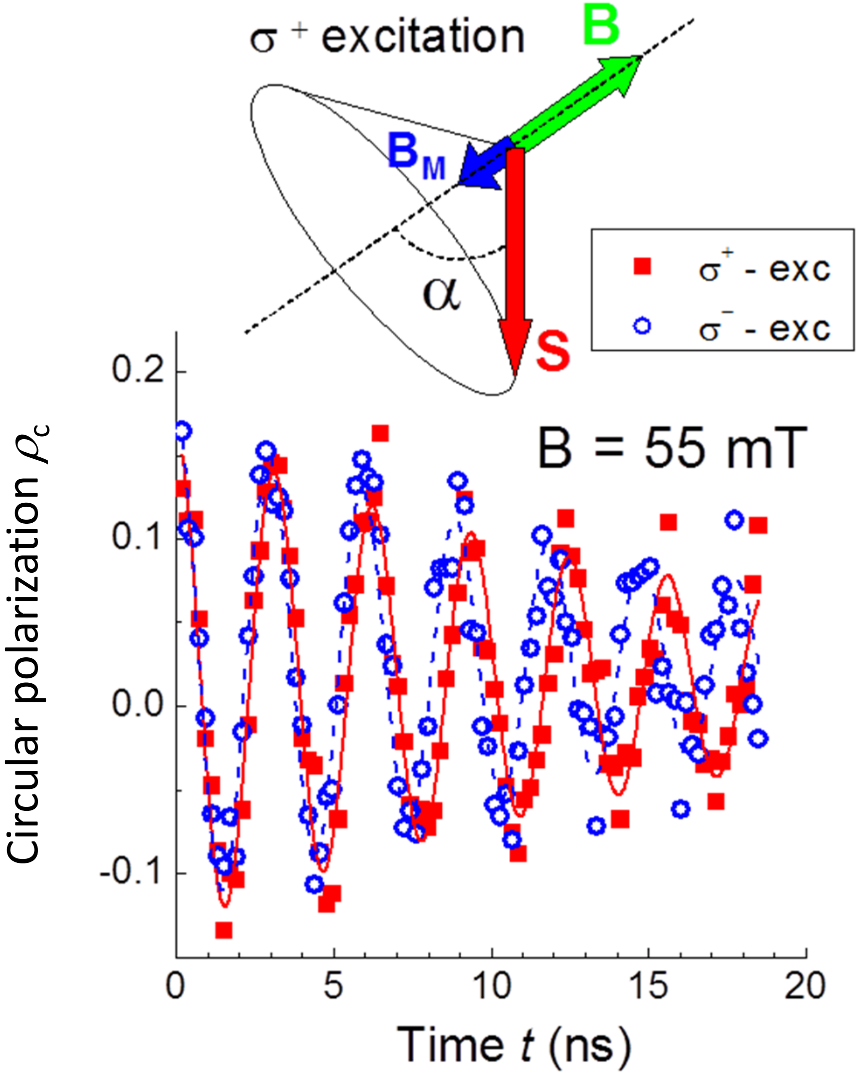
1. Lifetime τ = 100 ns

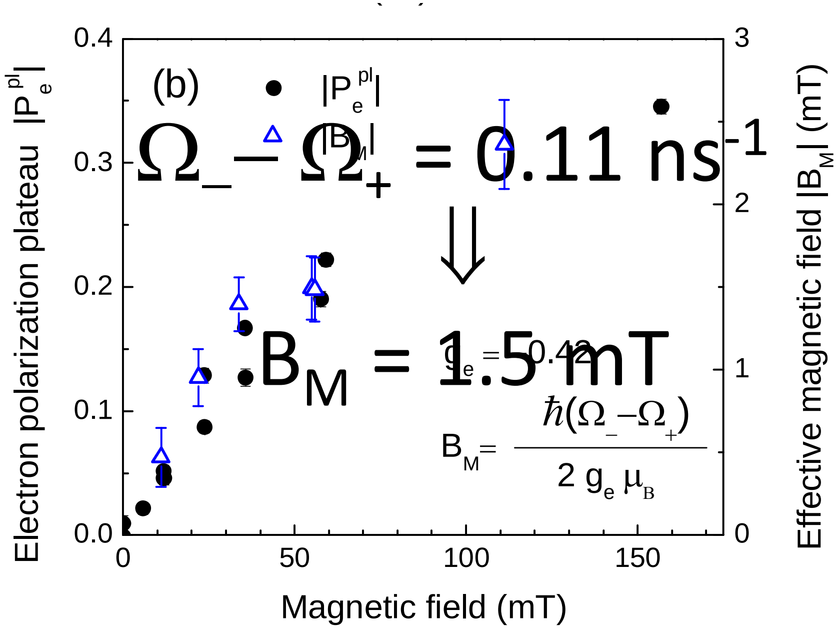


*PRB **80**, 081203(R) (2009)*

TRPL in oblique field

B_M – effective exchange field of Mn acting on electron.





$$\Omega_- - \Omega_+ = 0.11\ \text{ns}^{-1}$$

$$\Downarrow$$

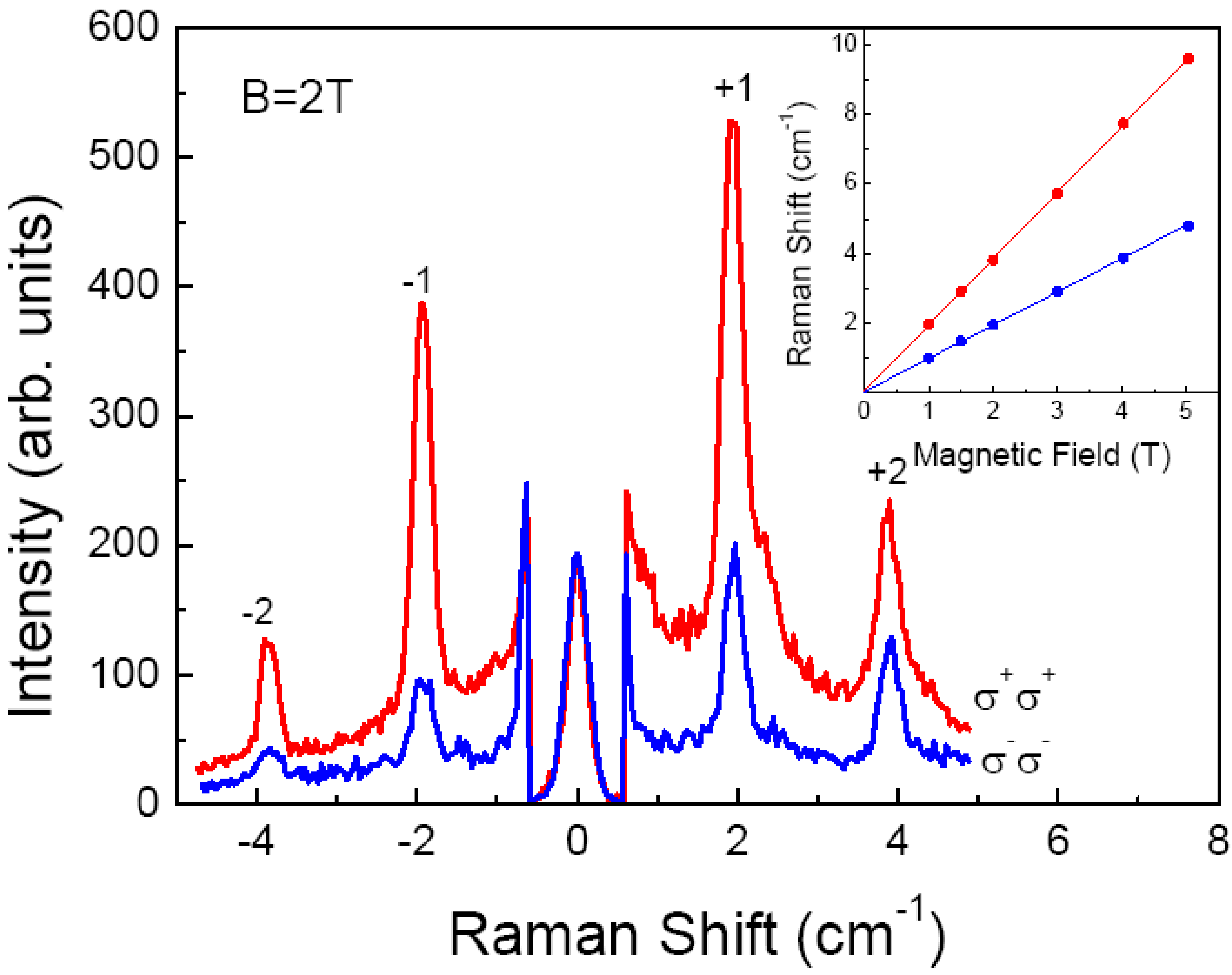
$$B_M = 1.5\ \text{mT}$$

Summary

1. Optical orientation of Mn ions is demonstrated (up to 25 %).

2. Weak longitudinal magnetic field (B ~ 100 mT) suppresses Mn^{2+} spin relaxation.

3. Oriented Mn^{2+} ions return spin polarization back to electron system providing a long-lived electron spin memory (up to 1 μs).

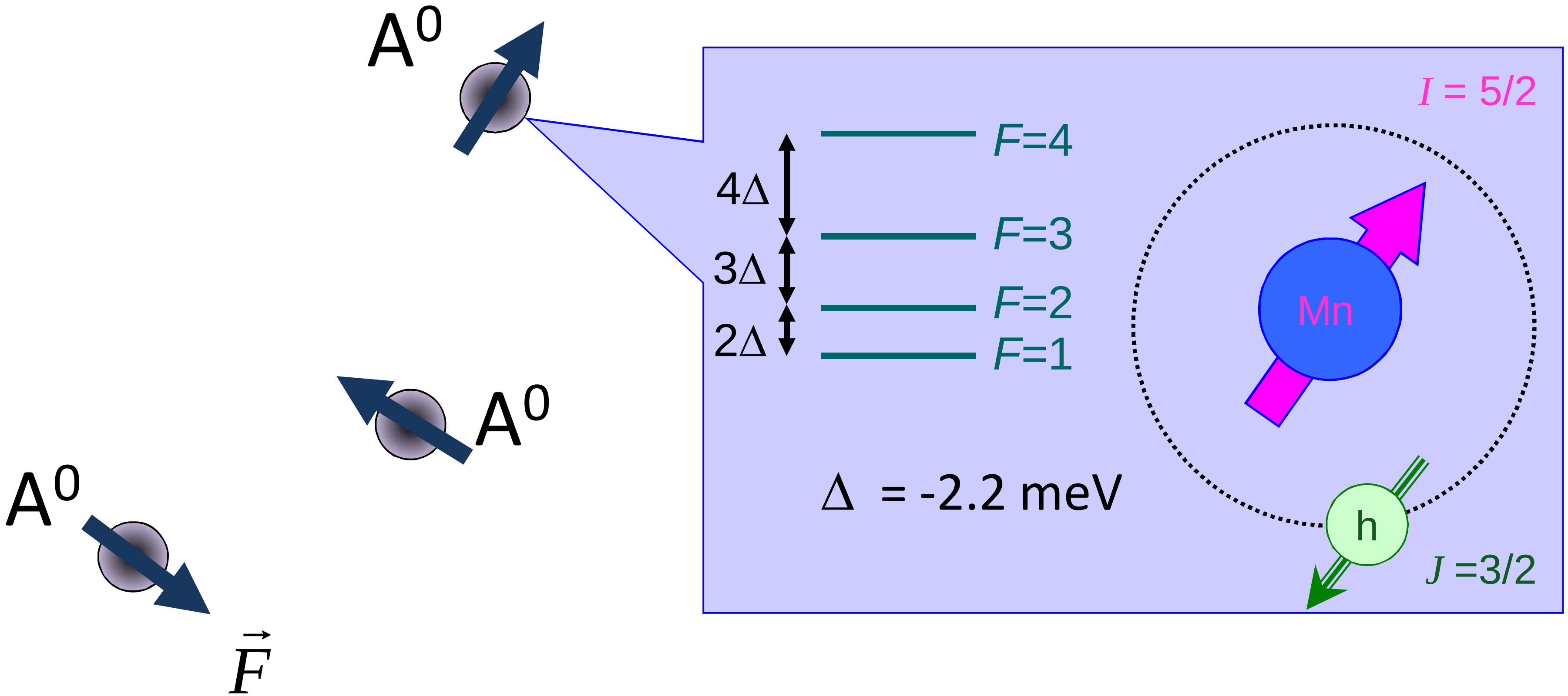


B=2T
-2
-1
+1
+2
$\sigma^+\sigma^+$
$\sigma^-\sigma^-$
Intensity (arb. units)
Raman Shift (cm^{-1})
Raman Shift (cm^{-1})
Magnetic Field (T)

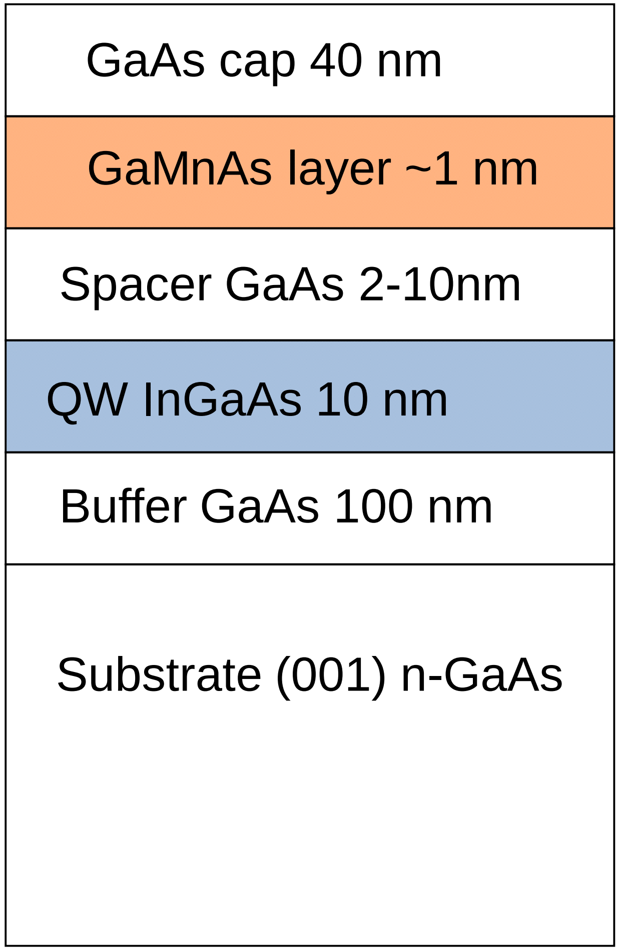
GaAs doped with low Mn concentration

Mn $3d^5 4s^2 \Rightarrow$ acceptor with $a_{B,A} \approx 1$ nm, $E_A \approx 110$ meV

$N_A \sim 10^{17}$-10^{18} cm^{-3}

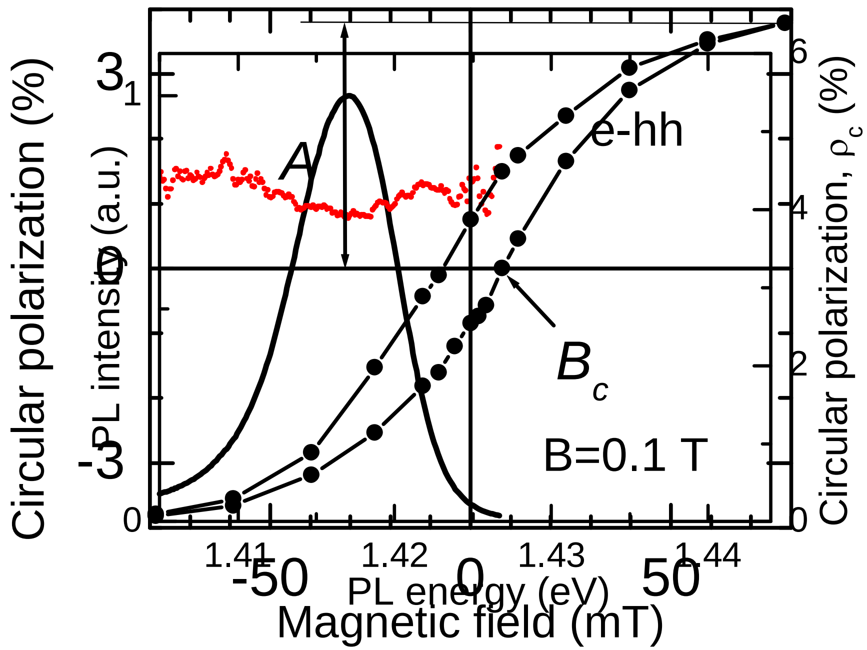


Ferromagnetic-Semiconductor Hybrid

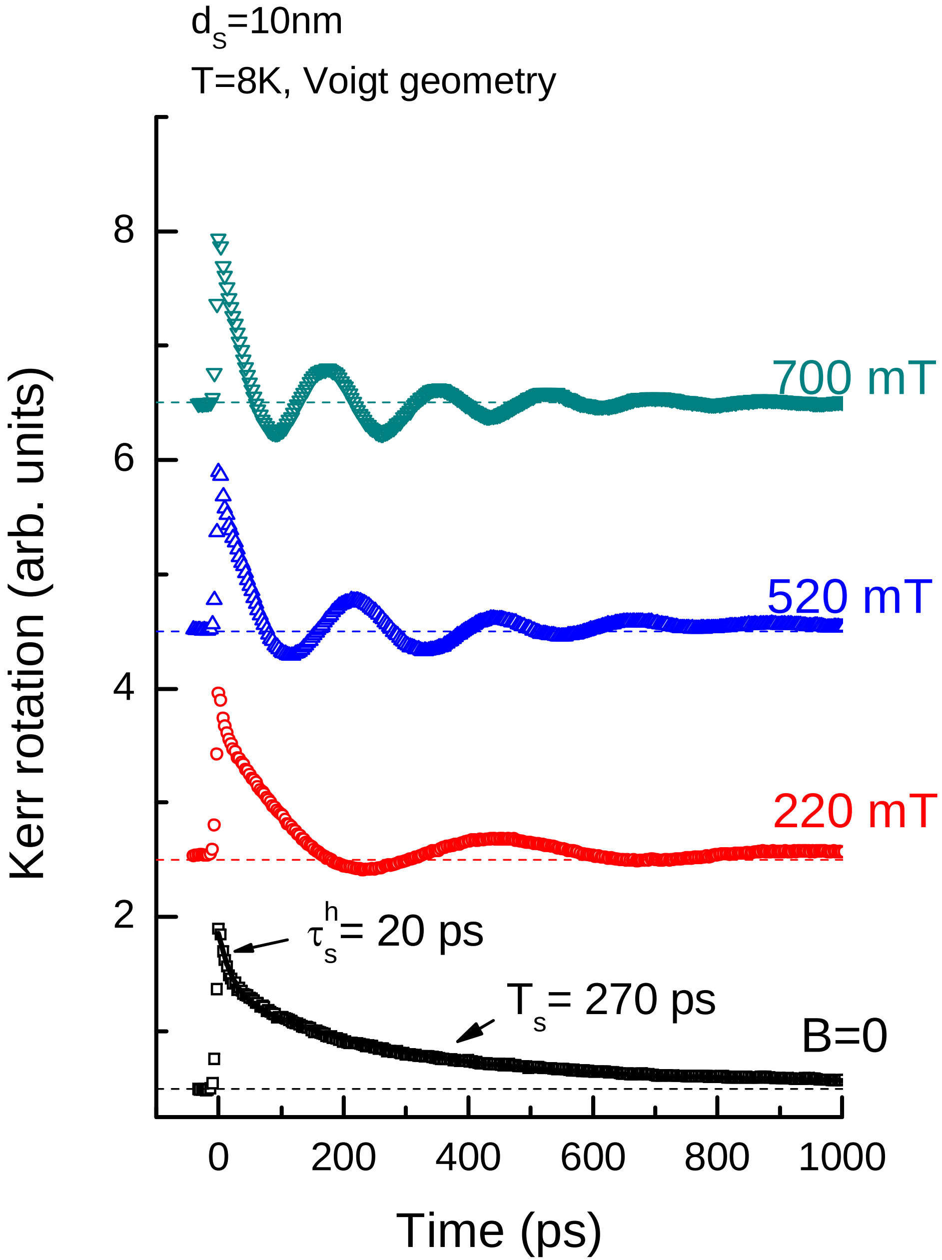


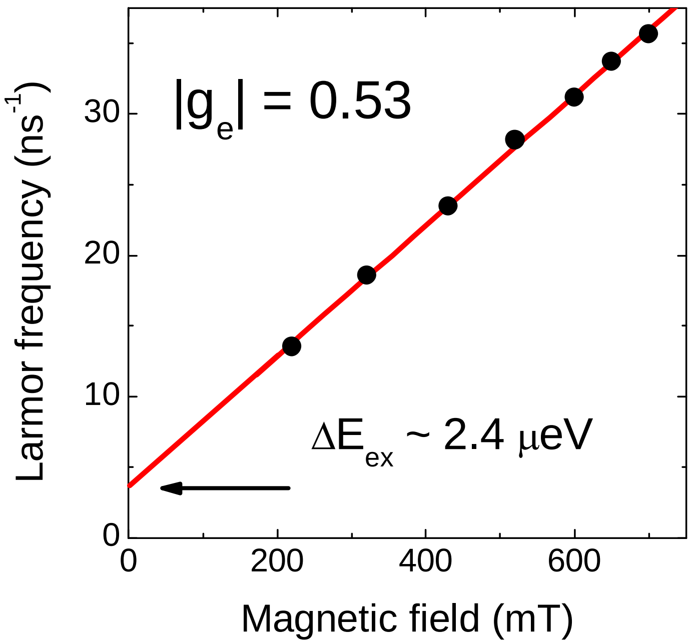
Ferromagnet

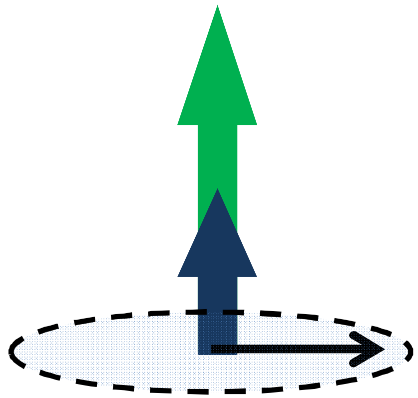
Semiconductor QW



Role of FM exchange field

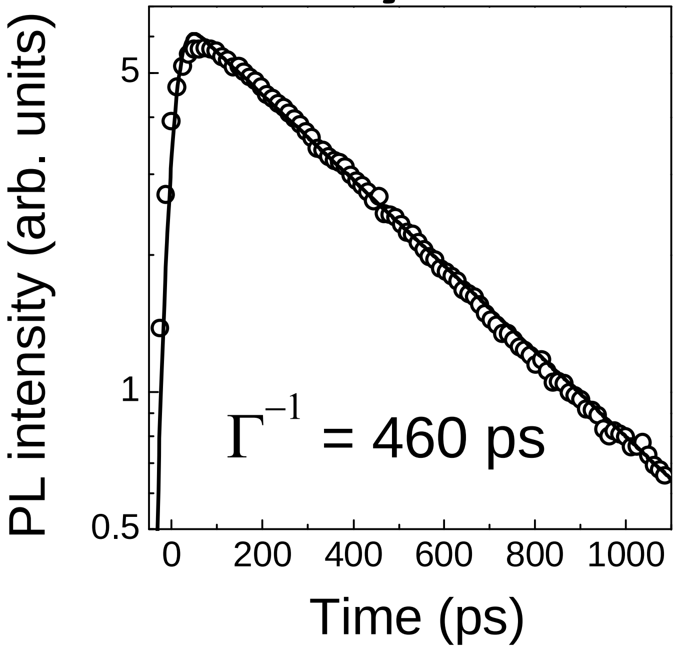


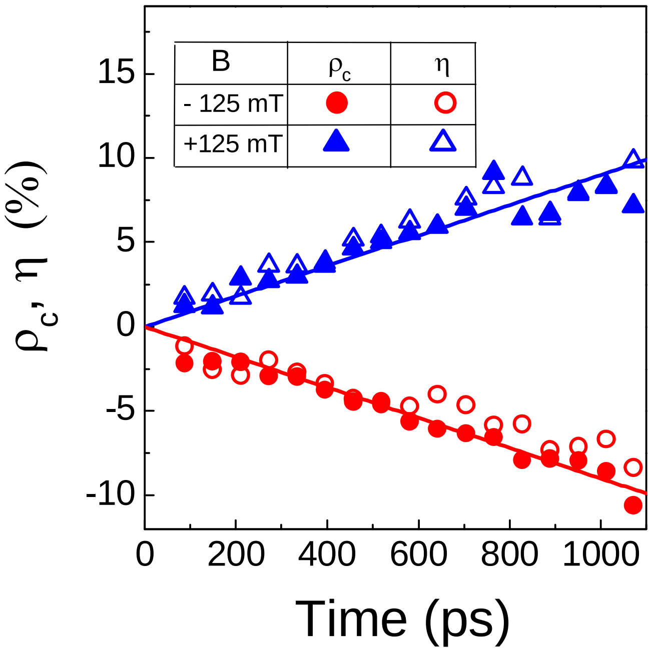




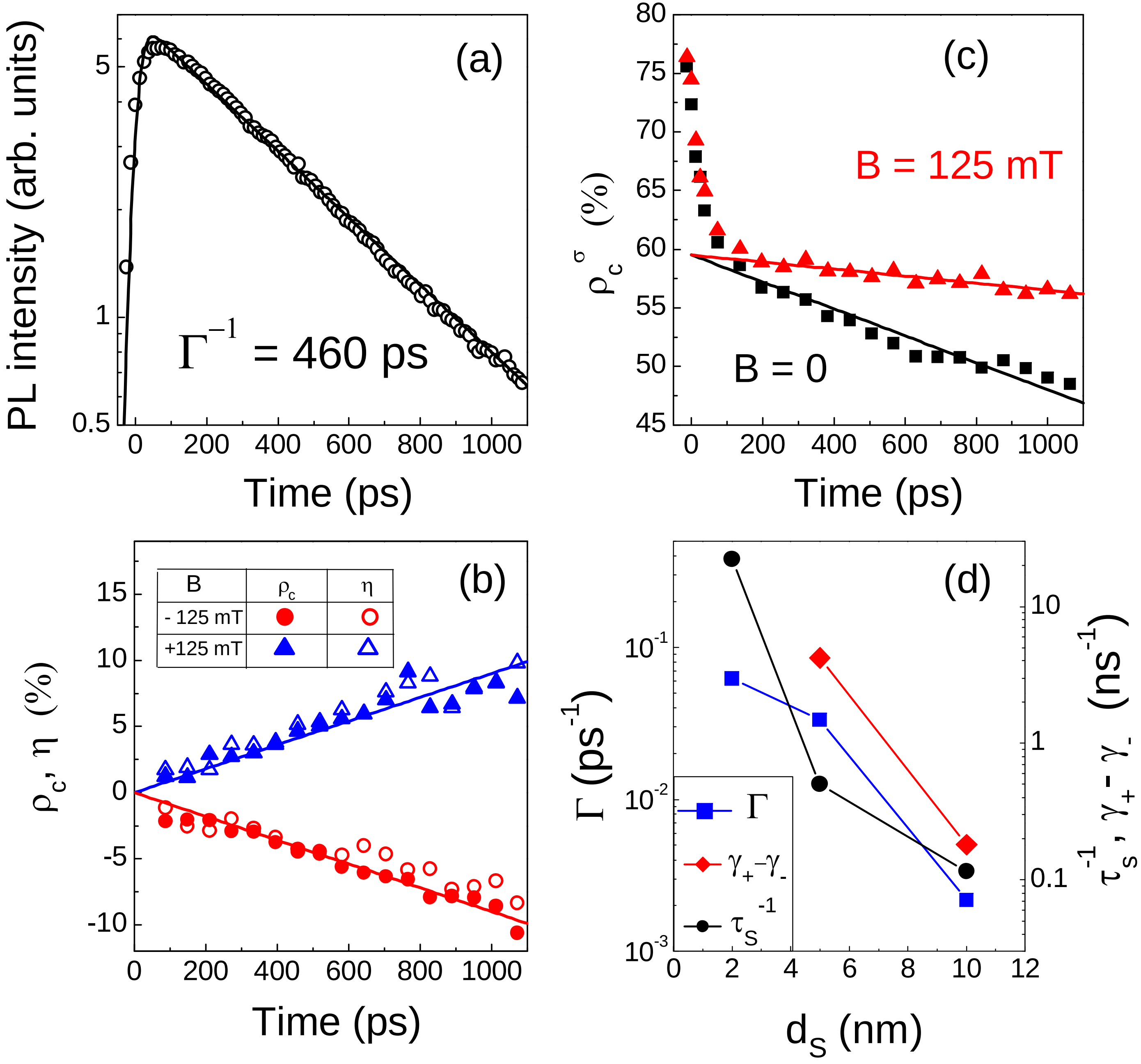
$B_{total} = B_M + B_{ext}$

Dynamics of spin separation effect



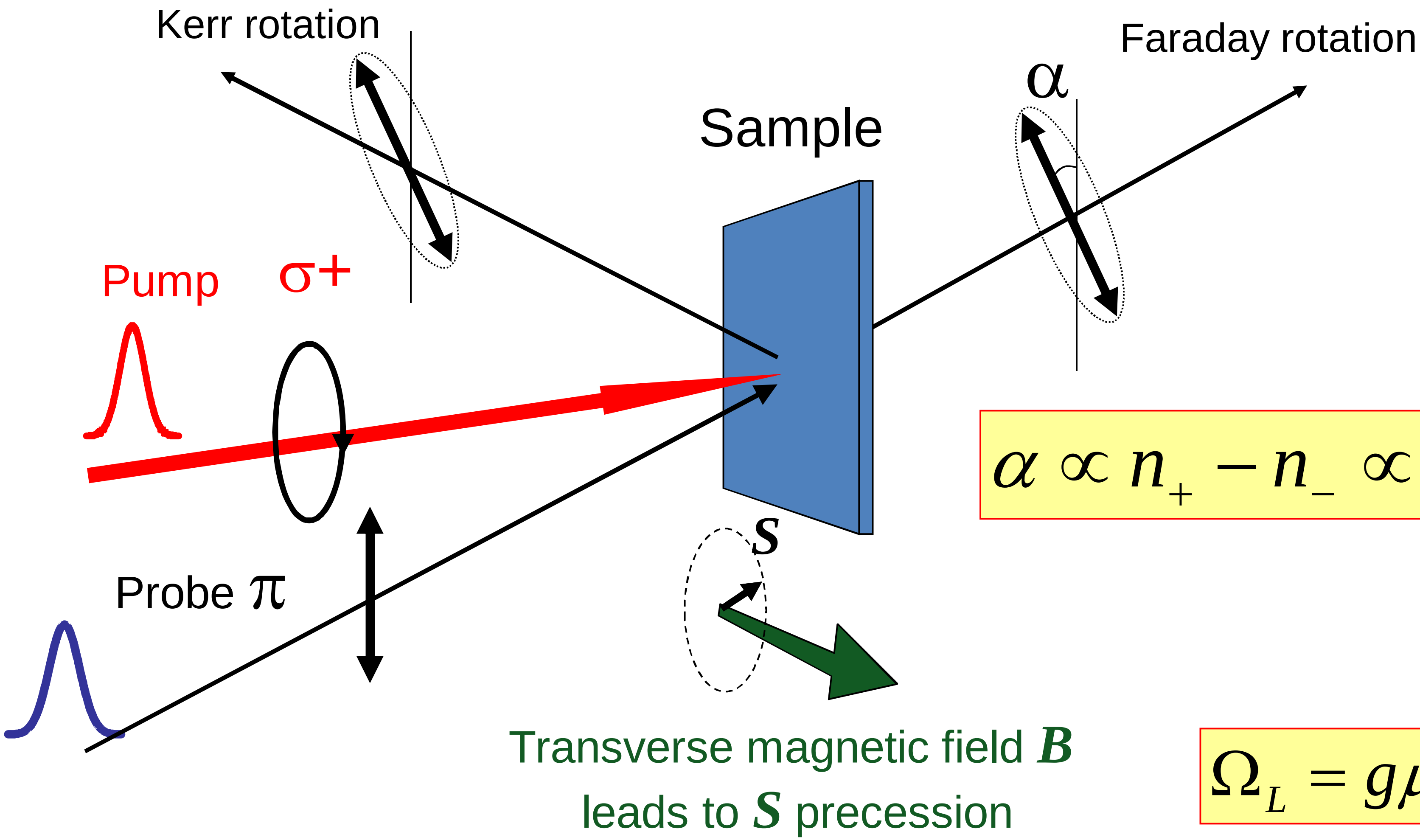


<u>Conclusion</u>: the spin polarization in Mn-based FM/QW hybrid is **<u>non-equilibrium</u>**



(a)
PL intensity (arb. units)
Γ^{-1} = 460 ps
Time (ps)
(c)
ρ_c^σ (%)
B = 125 mT
B = 0
Time (ps)
(b)
B
ρ_c
η
- 125 mT
+125 mT
ρ_c, η (%)
Time (ps)
(d)
Γ (ps^{-1})
τ_s^{-1}, $\gamma_+ - \gamma_-$ (ns^{-1})
Γ
$\gamma_+ - \gamma_-$
τ_S^{-1}
d_S (nm)

Time-resolved pump probe Faraday (Kerr) rotation

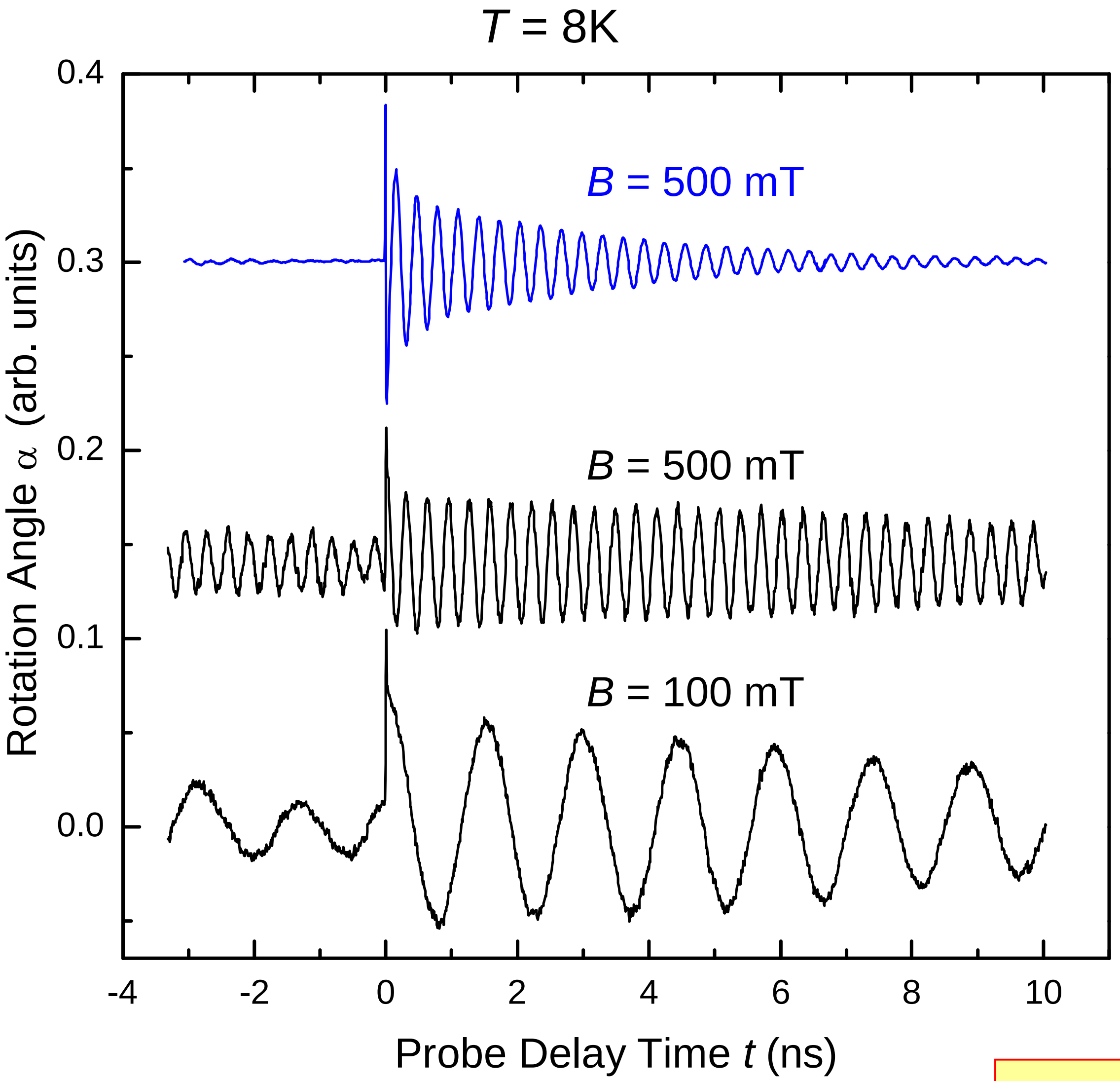


$$\alpha \propto n_+ - n_- \propto S_z$$

$$\Omega_L = g\mu_B B$$

$$\alpha(t) \propto \cos(\Omega_L t) e^{-t/T_2^*}$$

Pump probe Faraday (Kerr) – rotation in GaAs-Mn



Degenerate Kerr rotation @ **X**

$$\hbar\omega_{pump} = \hbar\omega_{probe} \approx E_X$$

$$T_2^* = 3\,\text{ns}$$

Two color Faraday rotation

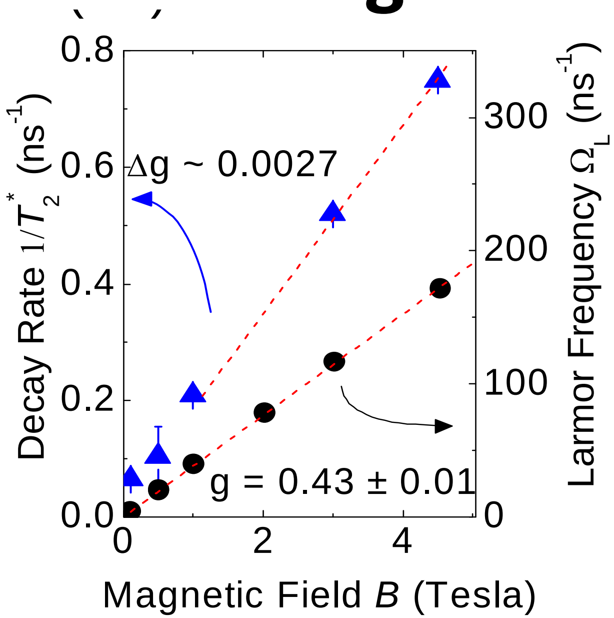
$$\hbar\omega_{pump} \approx E_g$$

$$\hbar\omega_{probe} < E_g$$

$$T_2^* = 16\,\text{ns}$$

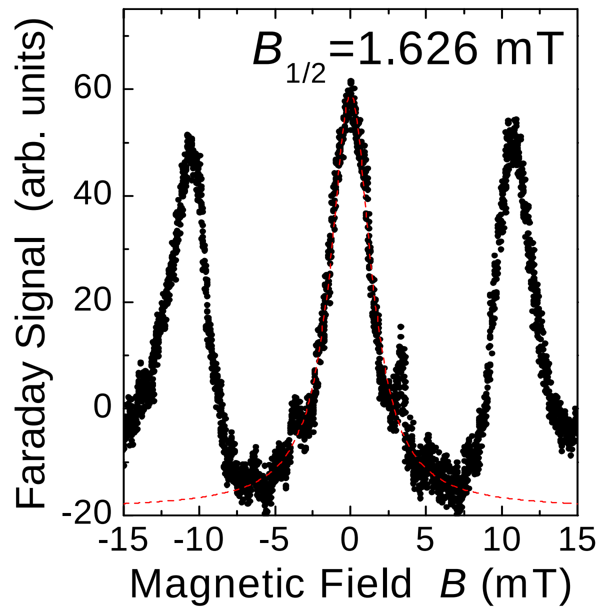
$$\alpha(t) \propto \cos(\Omega_L t) e^{-t/T_2^*}$$

g-factor and spin dephasing T_2^*



Electron g-factor

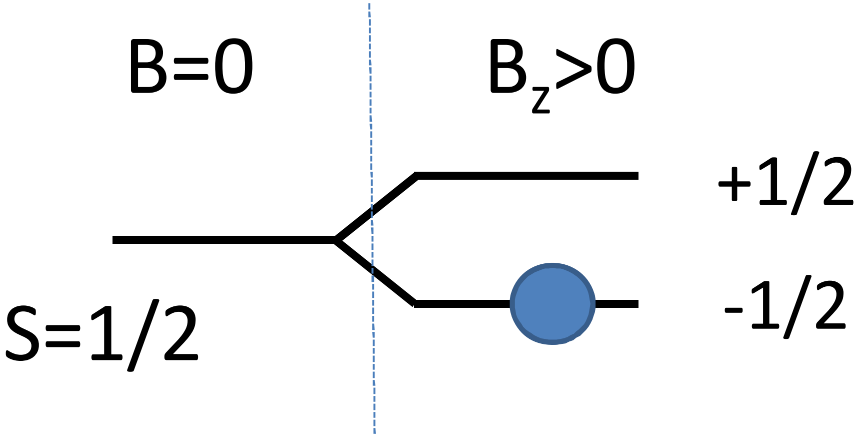
$$\frac{1}{T_2^*} = \frac{1}{T_2^*(0)} + \frac{\Delta g \mu_B B}{\sqrt{2}\hbar}$$



$$T_2^*(0) = 16\,\mathrm{ns}$$

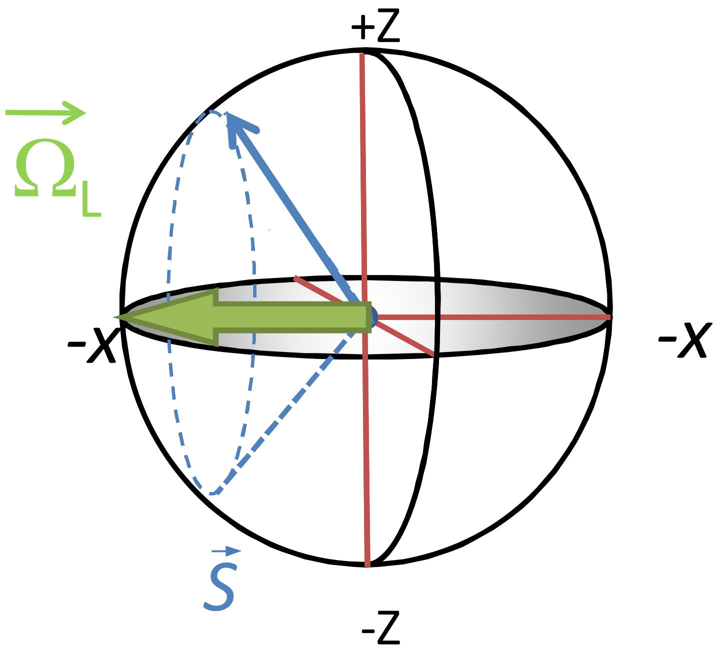
$$\frac{1}{T_2^*(0)} = \frac{1}{\tau} + \frac{1}{\tau_S}$$

Magnetic field induced spin polarization



$$kT << g\mu_B B$$

Equilibrium spin polarization due to the thermal population of spin levels split by the external magnetic field B



Spin precession in transverse magnetic field with Larmor frequency

$$\hbar\Omega_L = g\mu_B B$$

Electron Spin Relaxation in GaAs

The main electron spin relaxation mechanisms:

- Elliot-Yafet (EY) and Dyakonov-Perel' (DP)

  Spin-orbit interaction

- Bir-Aronov-Pikus (BAP)

  Electron-hole exchange interaction

- Hyperfine interaction with nuclear spins

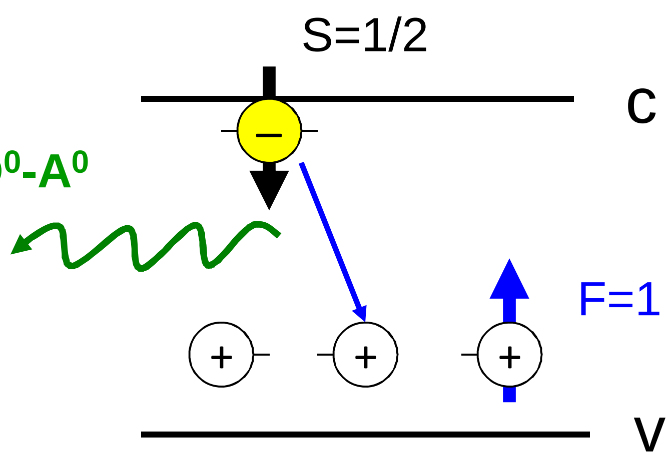
In bulk GaAs

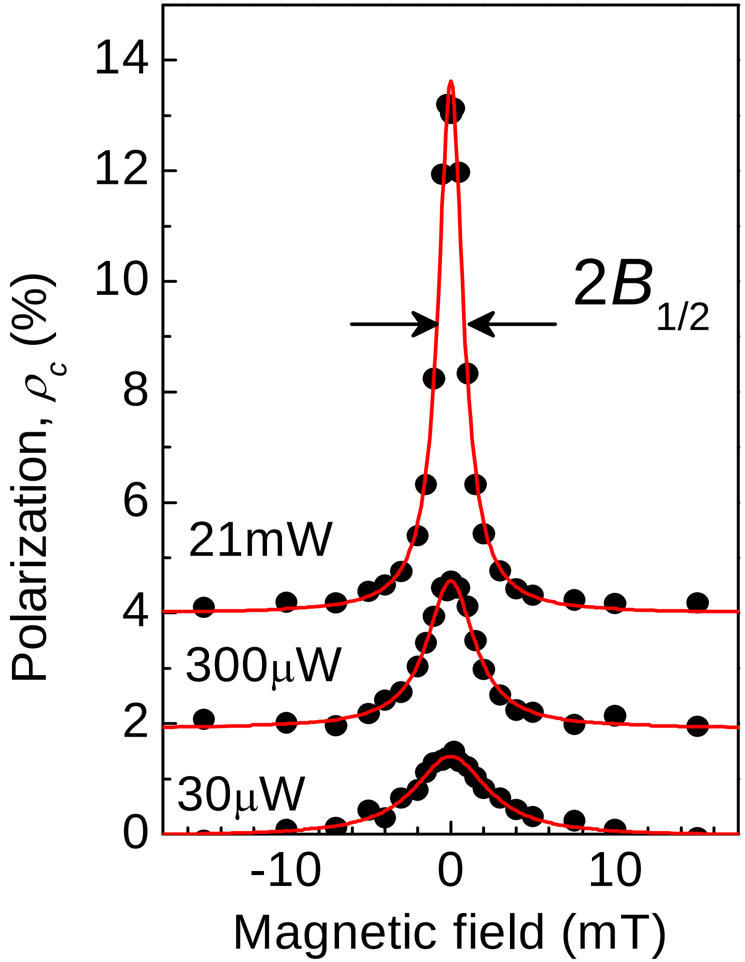
- *n*-type   DP and Hyperfine interaction, $\tau_S \leq 300$ ns
- *p*-type   BAP mechanism , $\tau_S \leq 5$ ns for $N_A \geq 10^{17}$ cm^{-3}

Hanle Effect for Mn-band emission in GaAs

Hanle halfwidth $$B_{1/2} = \frac{\hbar}{g_e \mu_B} \frac{1}{T_S}.$$

Electron spin relaxation τ_S ~ 20-100 ns





G.V. Astakhov et al., PRL **101**, 76602 (2008)