# Spin-flip Raman scattering in type-I quantum dots with direct and indirect band structure

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# Outline

- Spin-flip Raman scattering: **what for ?**
- Direct band-gap (In,Ga)As/GaAs quantum dots
  - → Symmetry-dependent scattering
  - → Electron *g* factor dispersion
  - → Exciton-cyclotron resonance-like complex
- Indirect band-gap (In,Al)As/AlAs quantum dots
  - → Γ-X-valley mixing
  - → Fine structure of indirect exciton

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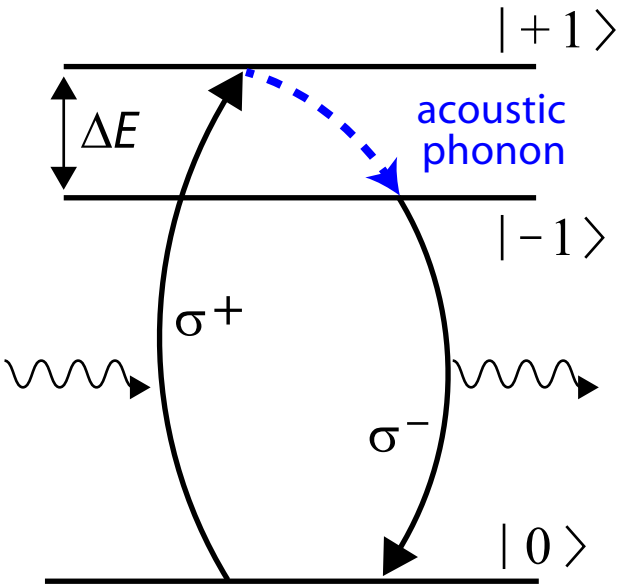
# Spin-flip Raman scattering: **what for ?**

- Resonant spin-flip Raman scattering (SFRS) is an inelastic light scattering process where the spin of a carrier / complex is reversed

Exciton spin-flip




- Scattering is governed by selection rules
  - → used to identify the spin-flip mechanism

**Raman shift**

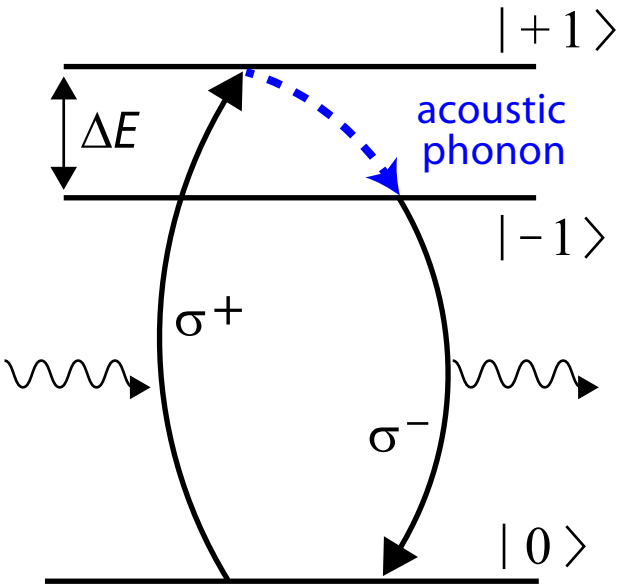
$$\Delta E = g\,\mu_B\,B$$

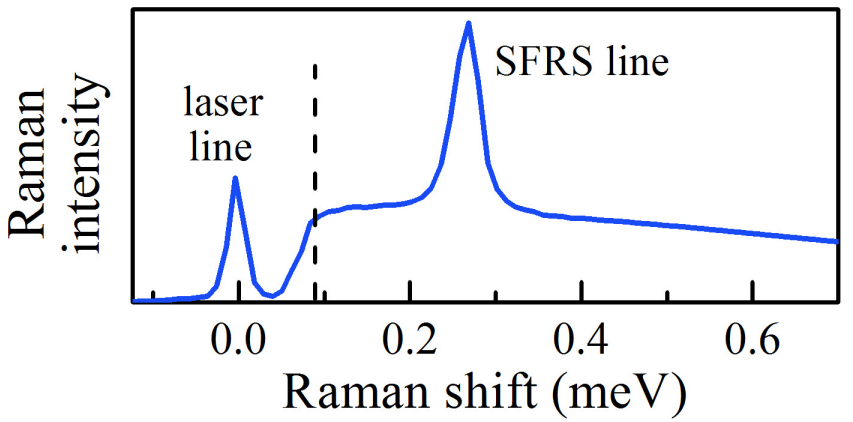
The shift of the spin-flip Raman line is proportional to *g* factor

# Spin-flip Raman scattering: **what for ?**

- Resonant spin-flip Ram
  scattering process whe

Exciton spin-flip

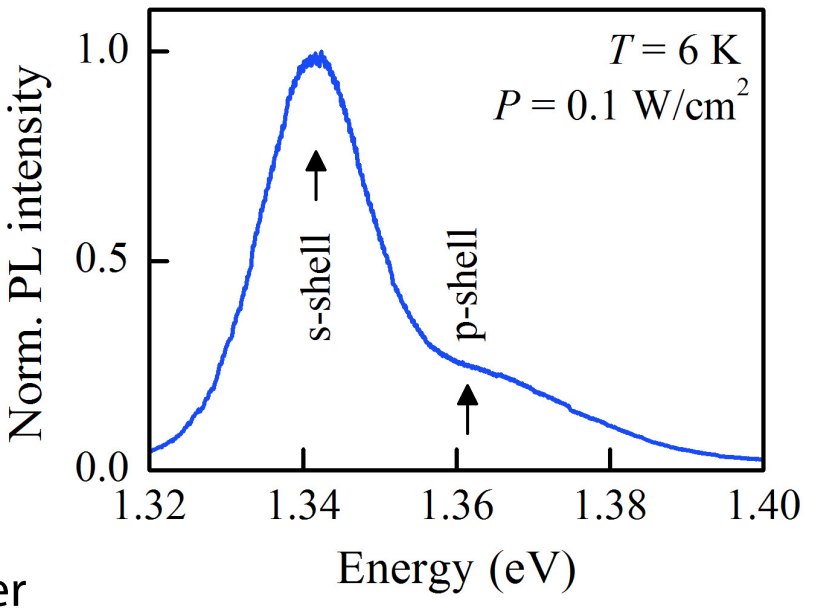


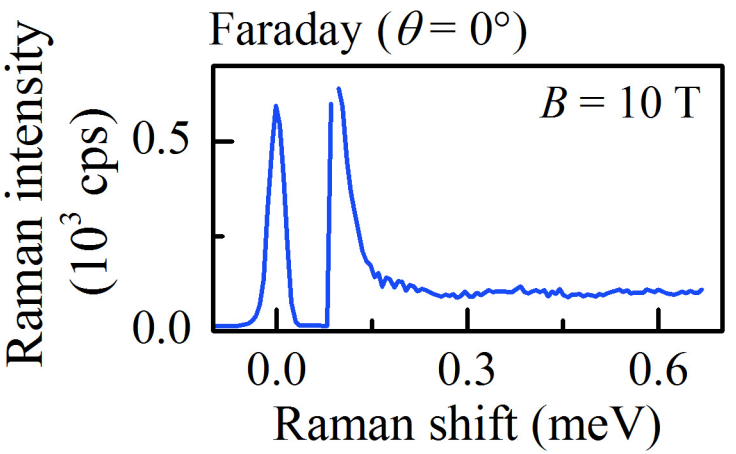

- Evaluation of spin structure of (e.g.) neutral and charged excitons
- Characterization of spin-based interactions

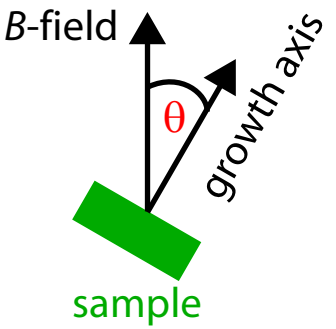
# Direct band-gap (In,Ga)As/GaAs QDs

- Grown on (001)-oriented GaAs substrate by MBE
- 20 layers of QDs, density of $10^{10}$ dots per $cm^2$
- Every dot contains one resident electron
- Dimension of dots: ~10 nm height, ~30 nm diameter

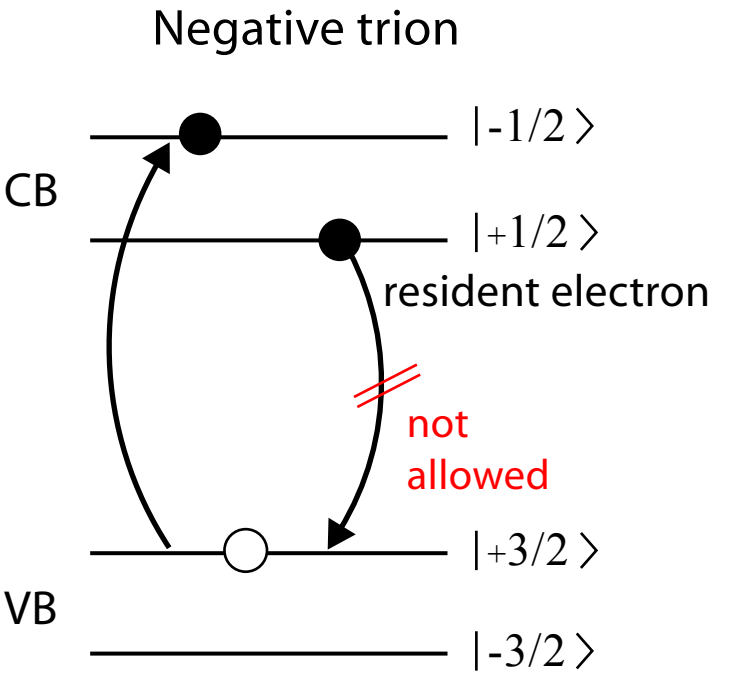


# Symmetry-dependent spin-flip scattering




- No SFRS line in Faraday geometry



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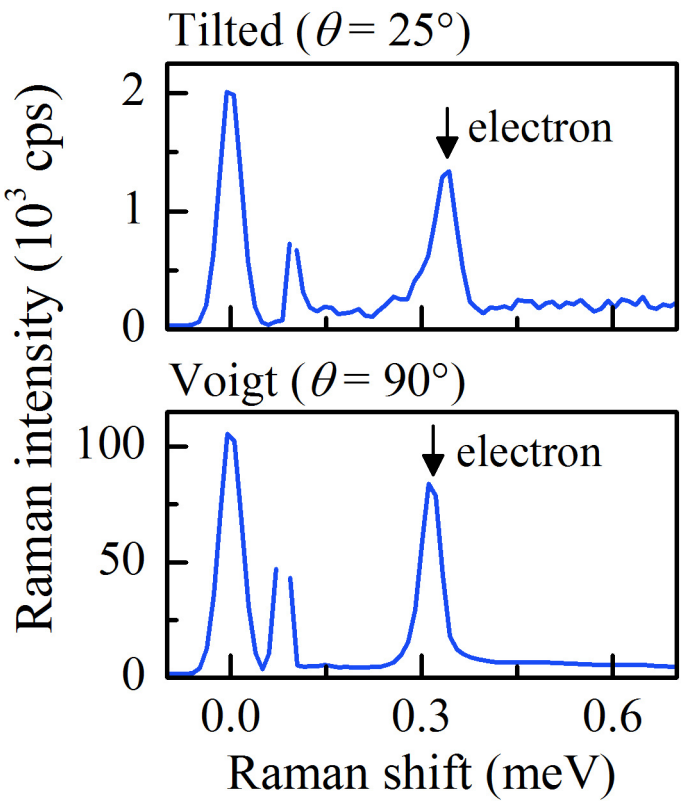
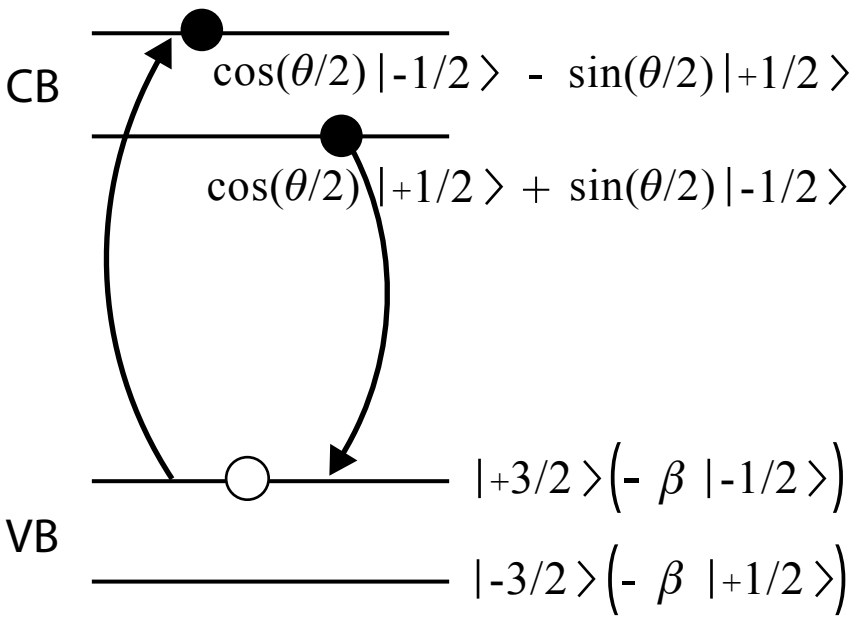
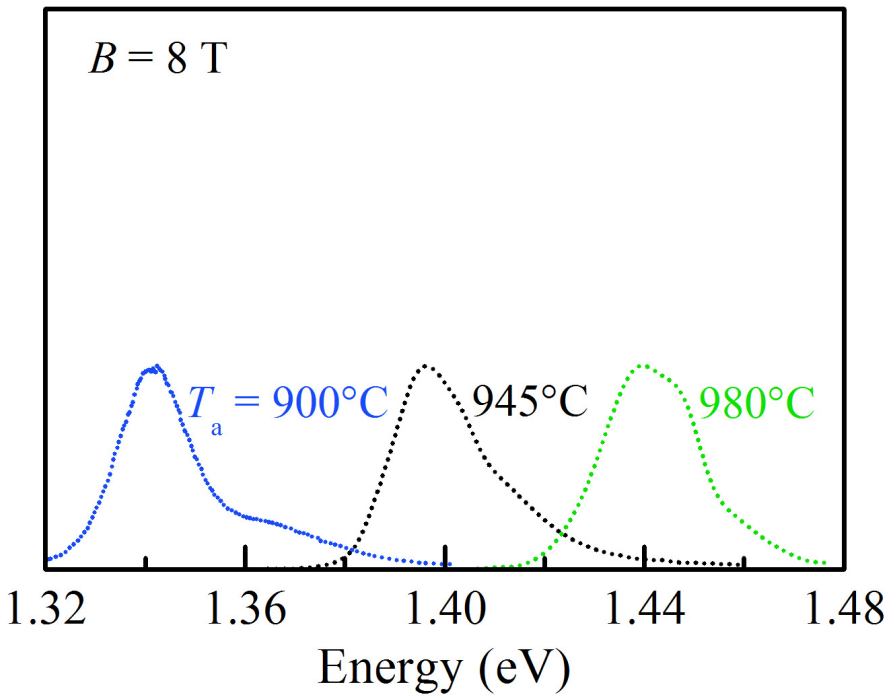



- Electron-SFRS in negative trion allowed due to state mixing



# Electron *g* factor dispersion

for three (In,Ga)As/GaAs QD samples




- Photoluminescence dependent on In/Ga-concentration, annealing temperature $T_a$

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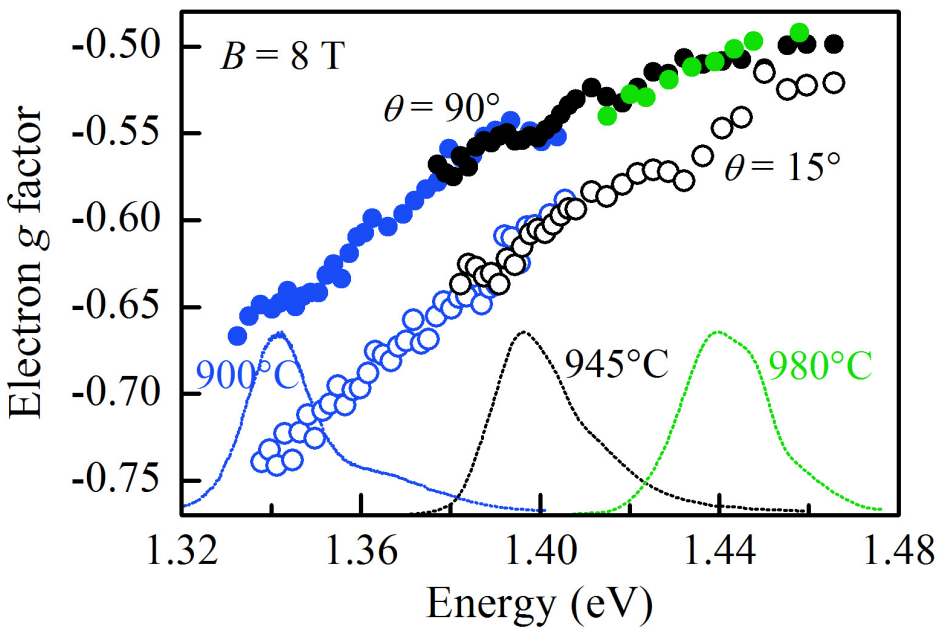


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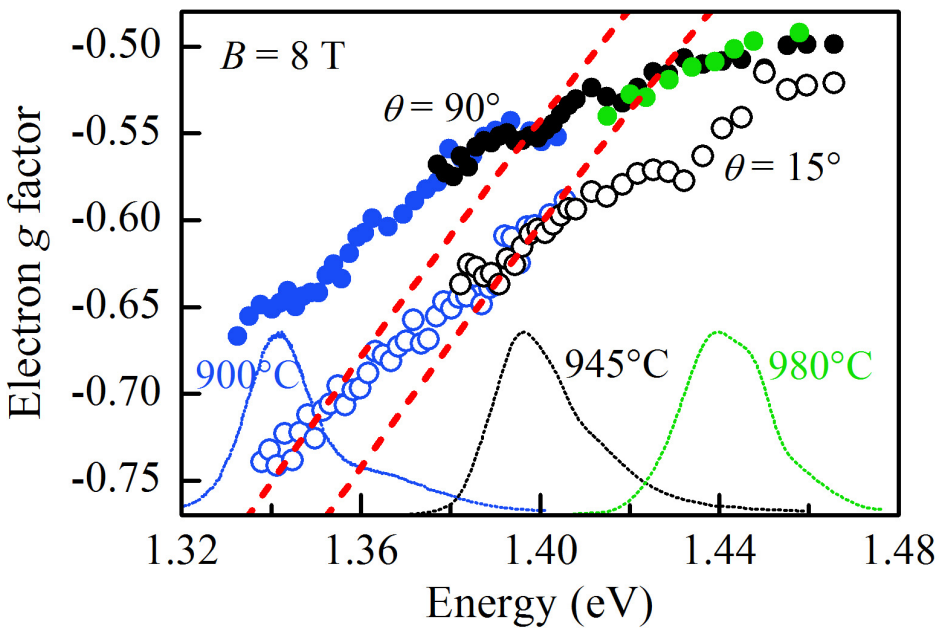


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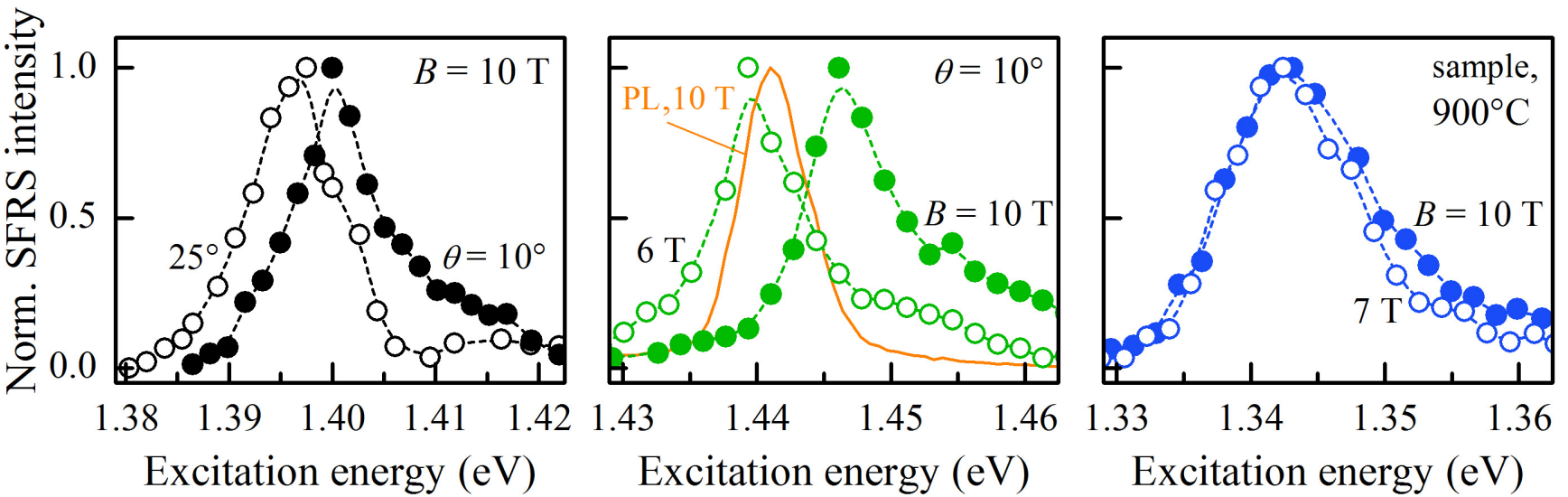
$$g_e \sim g_0 \left[ 1 - \frac{E_p}{3} \frac{\Delta_{so}}{E_g (E_g + \Delta_{so})} \right]$$

# Involvement of excited electron states in SFRS

Resonance profiles of electron spin-flip intensity

**Dependencies:**

- Tilting angle $\theta$
- Magnetic field $B$
- QD size



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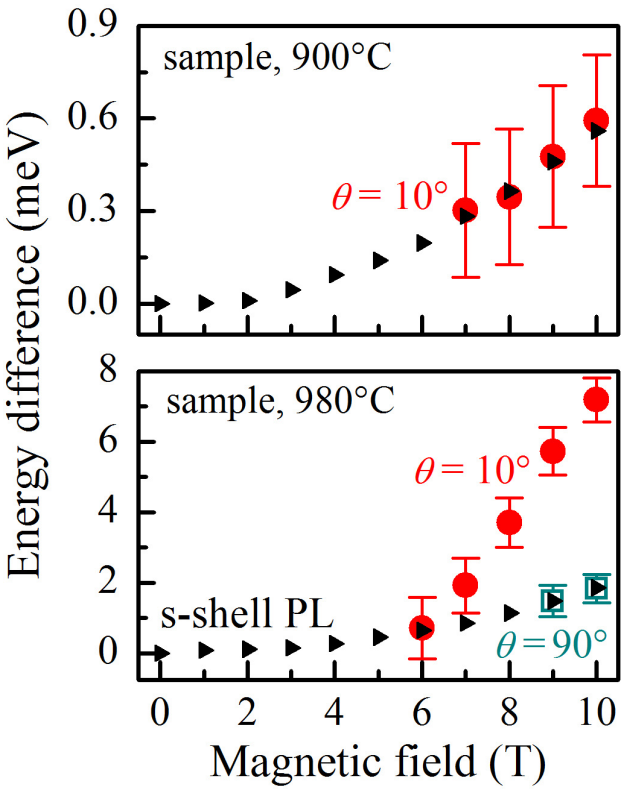
*Linear* shift of profiles is larger than diamagnetic shift of s-shell PL




Three-step SFRS process similar to

→ **exciton-cyclotron resonance**
as observed in quantum wells

1. Resonant excitation of excited $T^-$ complex:

$$|\uparrow\rangle_{n=0}\ |\downarrow\Uparrow\rangle_{n\neq 0}$$

2. Spin exchange between electrons

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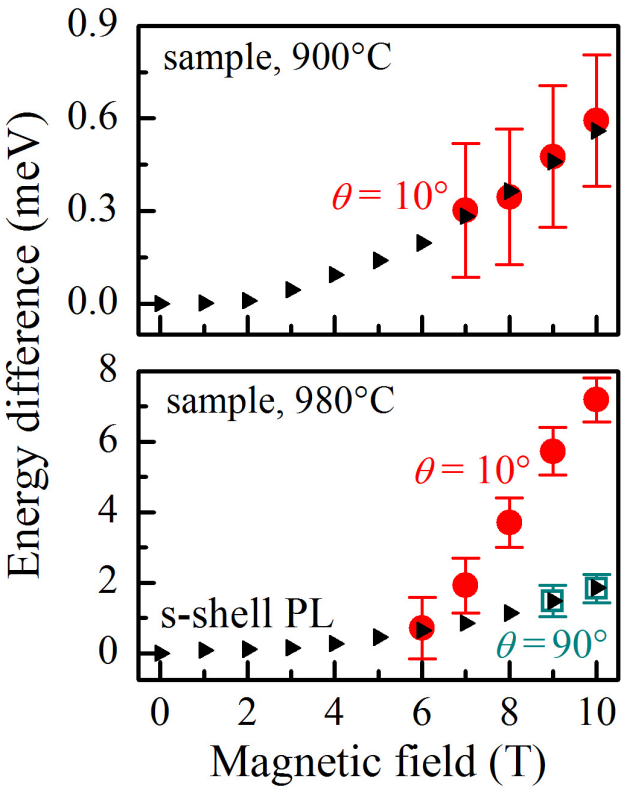


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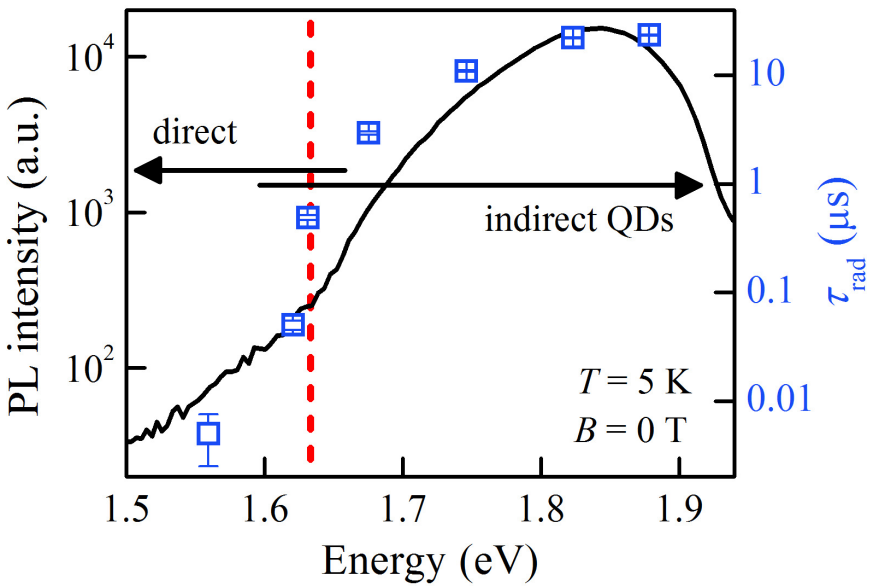
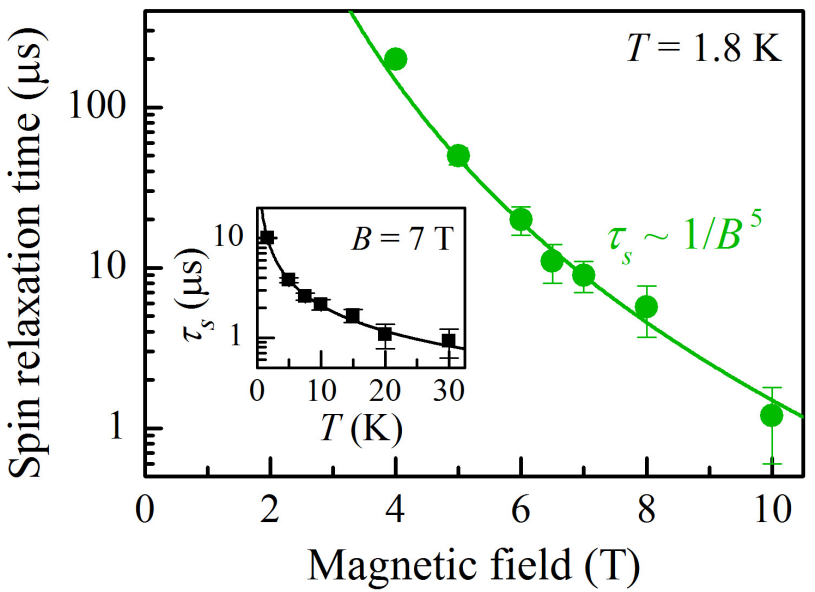
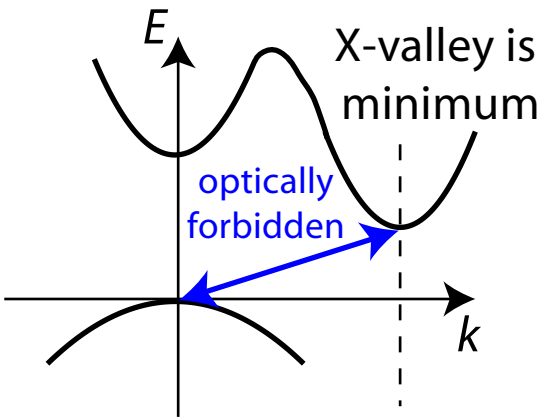
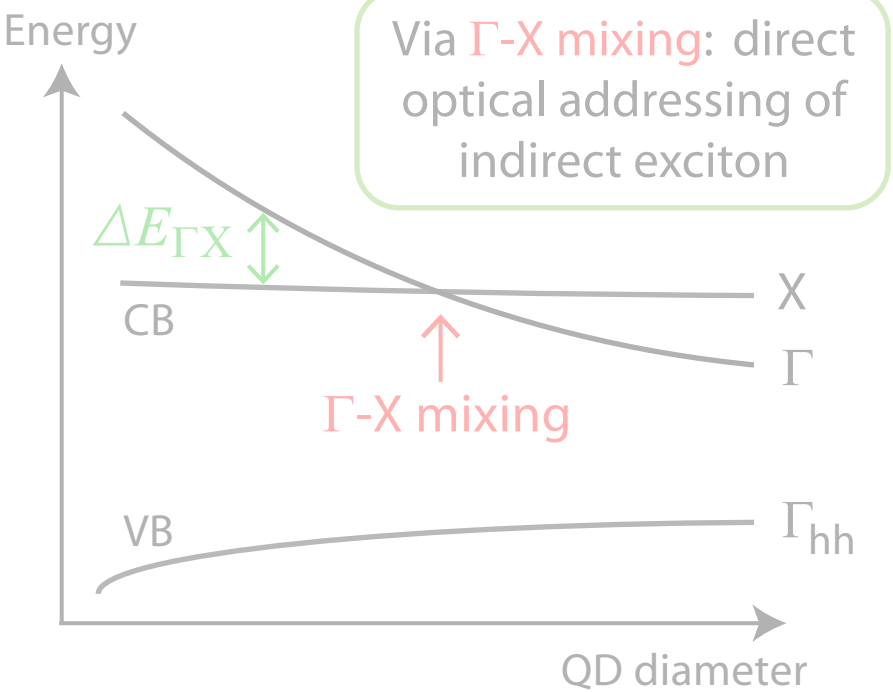


# Novel (In,Al)As/AlAs QD ensembles

- Indirect band gap

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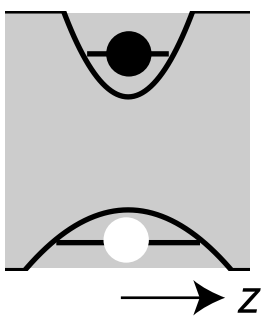

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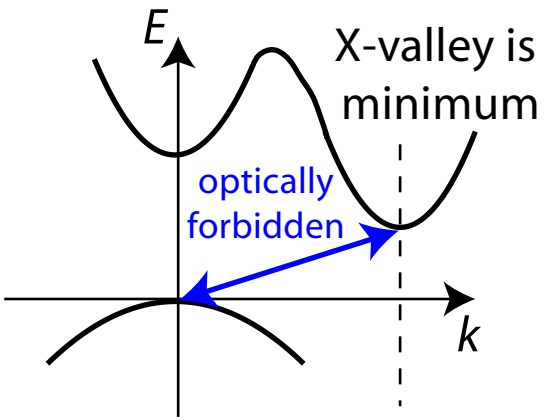


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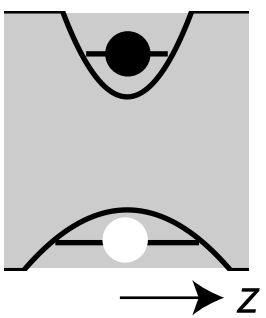
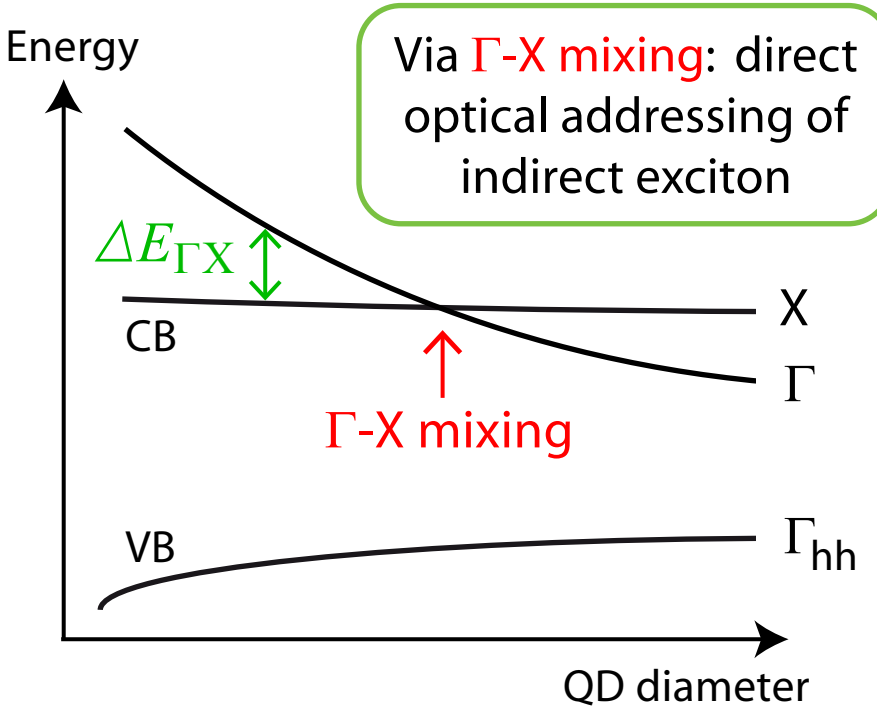
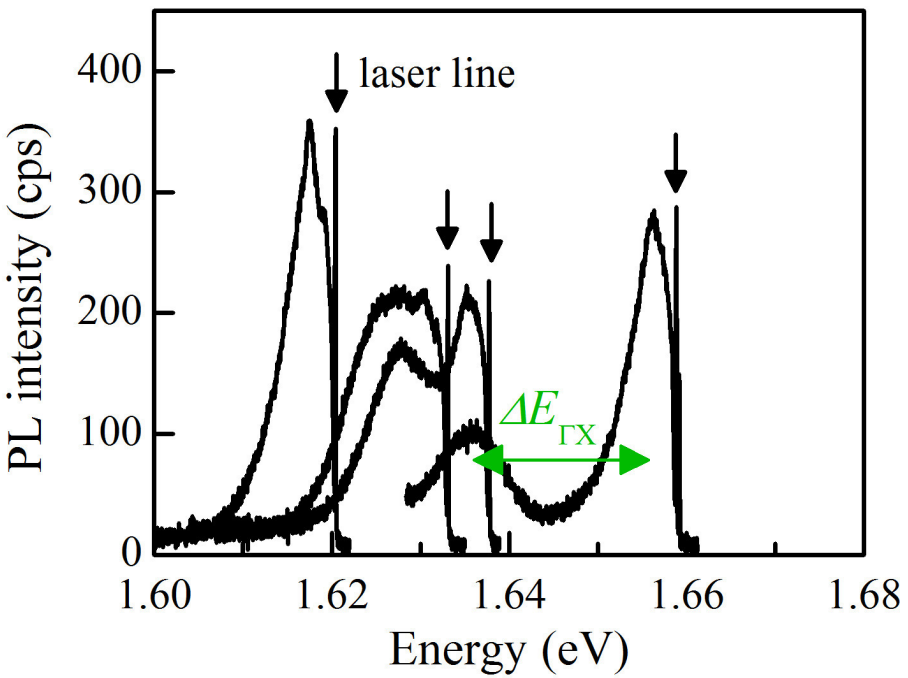
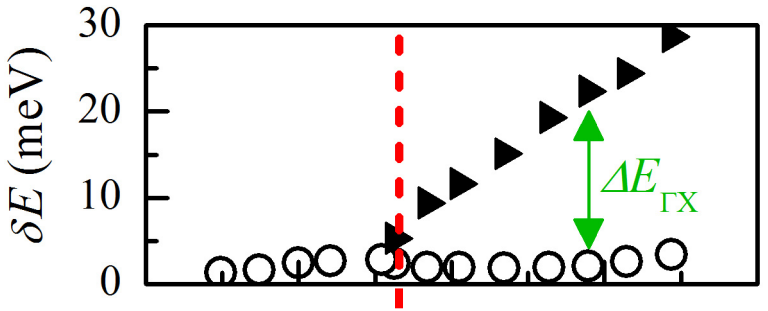


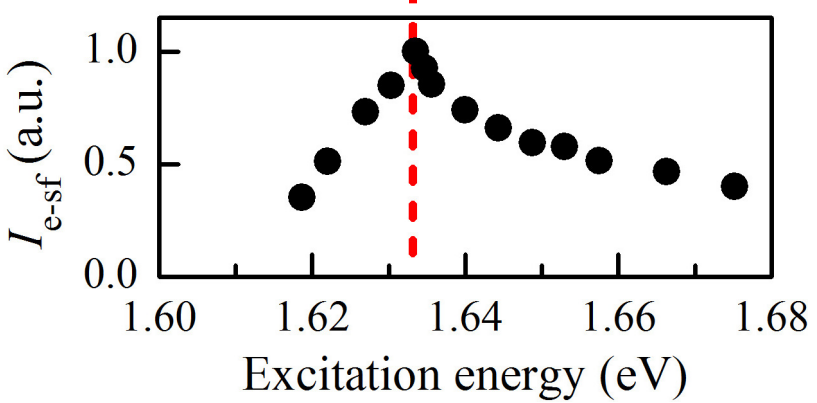
# Revelation of Γ-X mixing

Resonant photoluminescence




Level crossing determined by electron-SFRS resonance profile

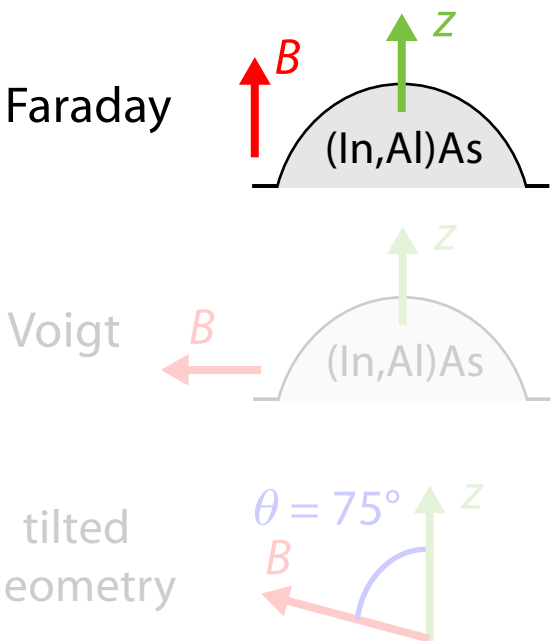


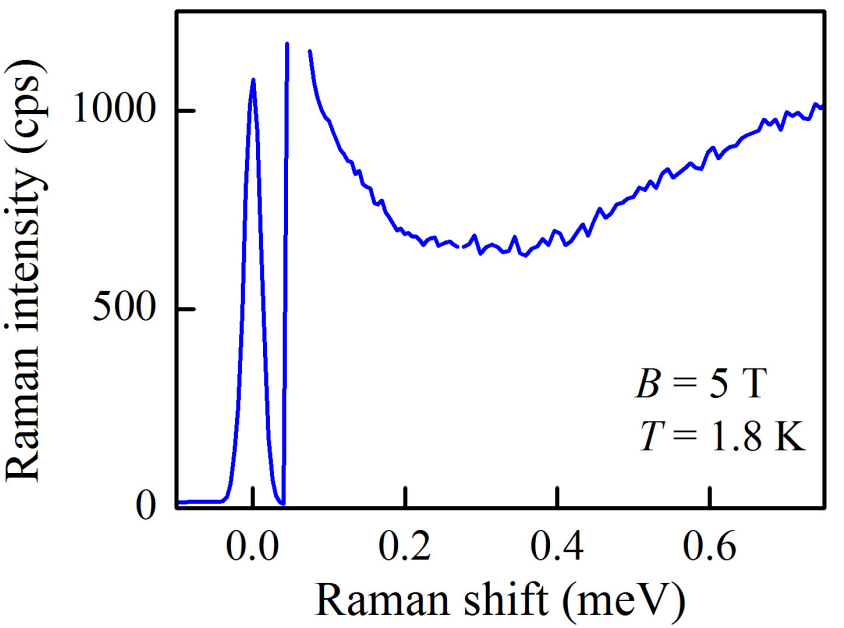
# Fine structure of indirect exciton

- Evaluation of *g* factor tensor

$$\begin{pmatrix} g_{xx} & 0 & 0 \\ 0 & g_{yy} & 0 \\ 0 & 0 & g_{zz} \end{pmatrix}$$

→ Angle dependence of SFRS



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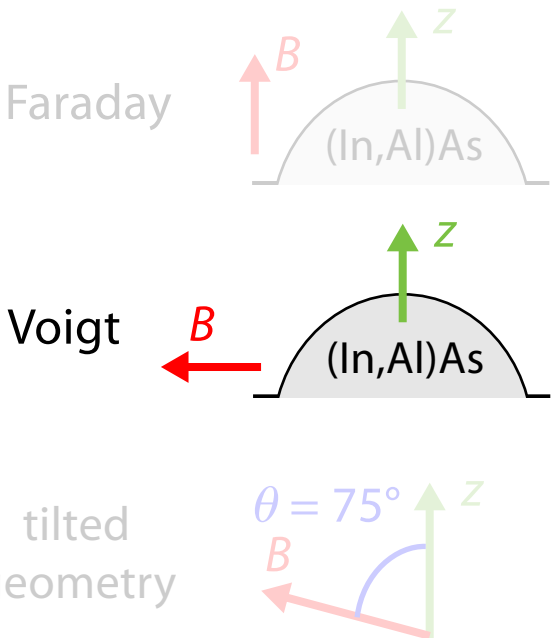


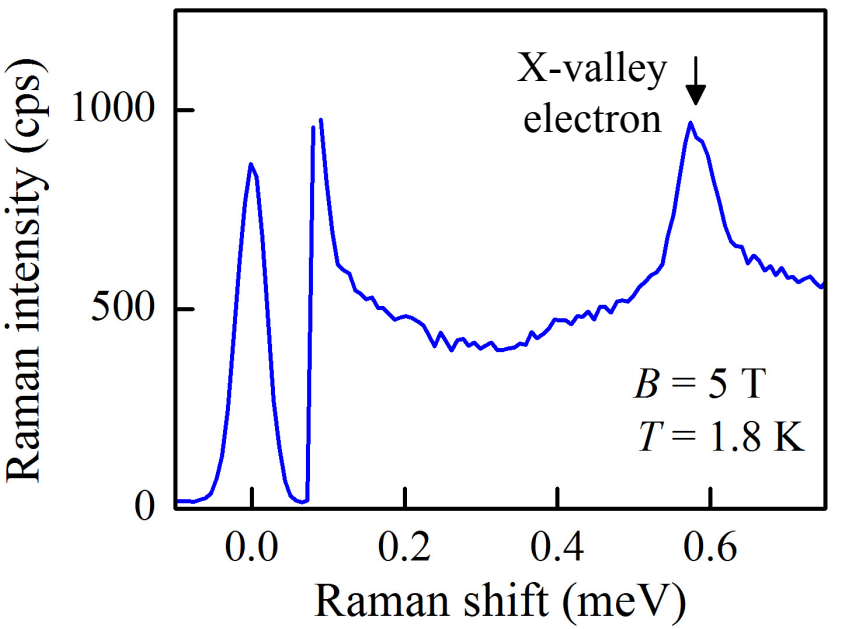

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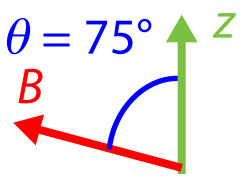
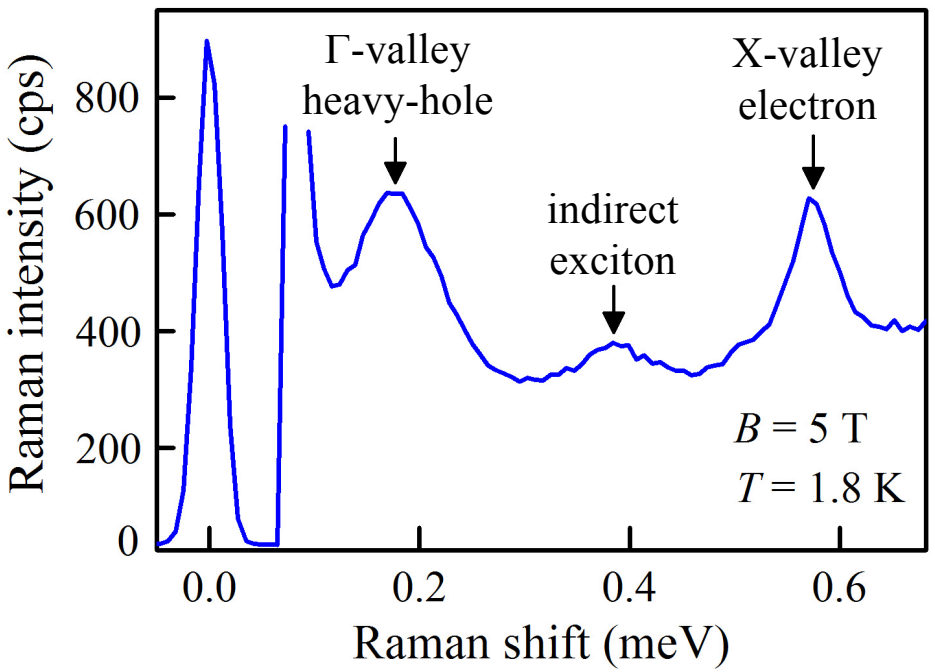
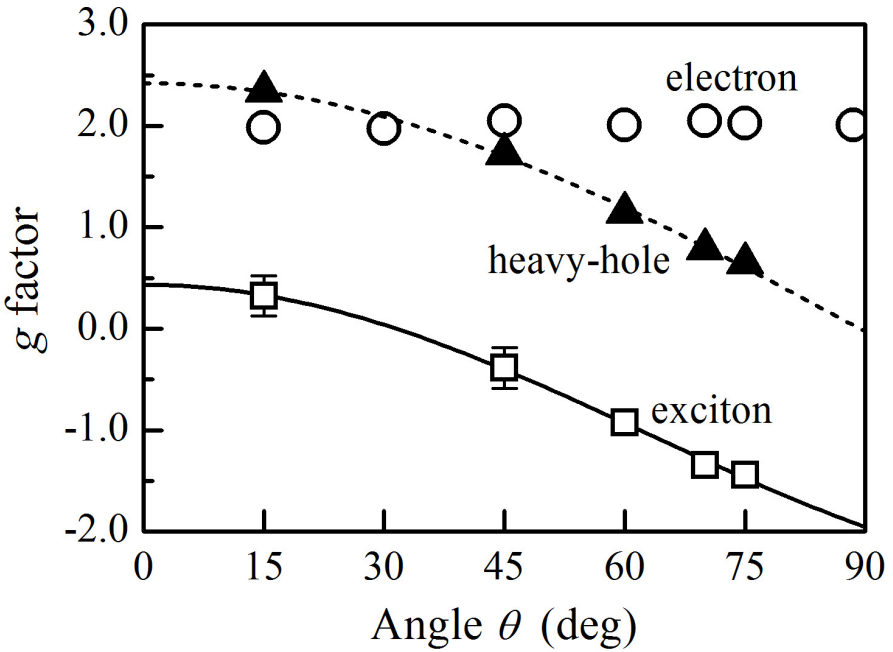
tilted geometry



# *g* factor characteristics




- X-valley electron

$$g_e^{\parallel} = g_e^{\perp} = 2.00 \pm 0.01$$

negligible spin-orbit interaction

$$\Delta g \sim \frac{\Delta_{so}}{E_g^2} \rightarrow 0$$

large band gap at X-point

- Γ-valley heavy-hole

$$g_{hh}^{\parallel} = 2.42 \pm 0.05 \ , \quad g_{hh}^{\perp} = 0.03 \pm 0.05$$

no light-heavy-hole mixing

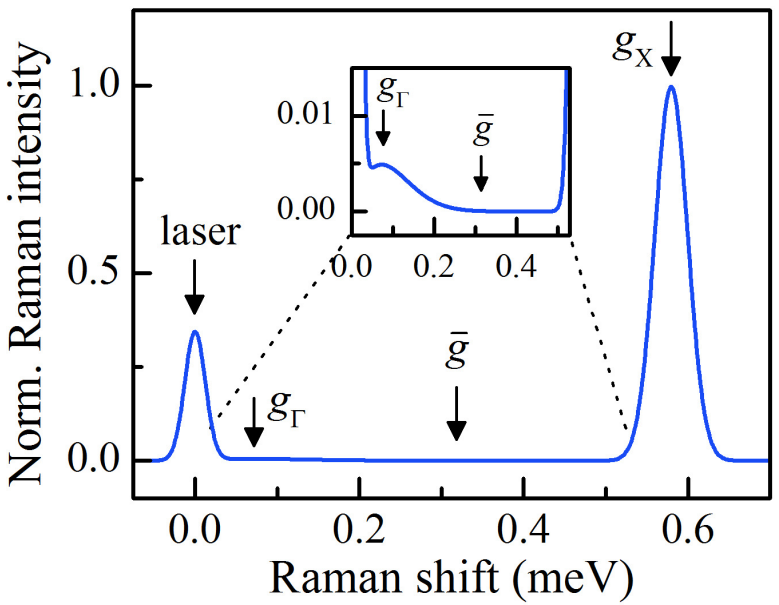
isotropic localization potential

- Indirect exciton

$$g_{Ex}^{\parallel} = 0.43 \pm 0.08 \ , \quad g_{Ex}^{\perp} = -1.95 \pm 0.08$$

# No signature from Γ-valley electron or exciton ??

- In Γ-X-mixing regime: $\Psi_e \sim |\Gamma\rangle + |X\rangle$ → SFRS line for $g_\Gamma$ or average $g$ factor
- Simulated SFRS spectrum:




small $g_\Gamma$ factor ↔ small Raman shift

large dispersion ↔ broad SFRS line

short lifetime of Γ-valley electron ↔ weak intensity

# Conclusion & Outlook

**SFRS in ...**

... direct band-gap (In,Ga)As/GaAs QDs

- Electron *g* factor dispersion over wide spectral range
- Observation of exciton-cyclotron resonance-like complex

... indirect band-gap (In,Al)As/AlAs QDs

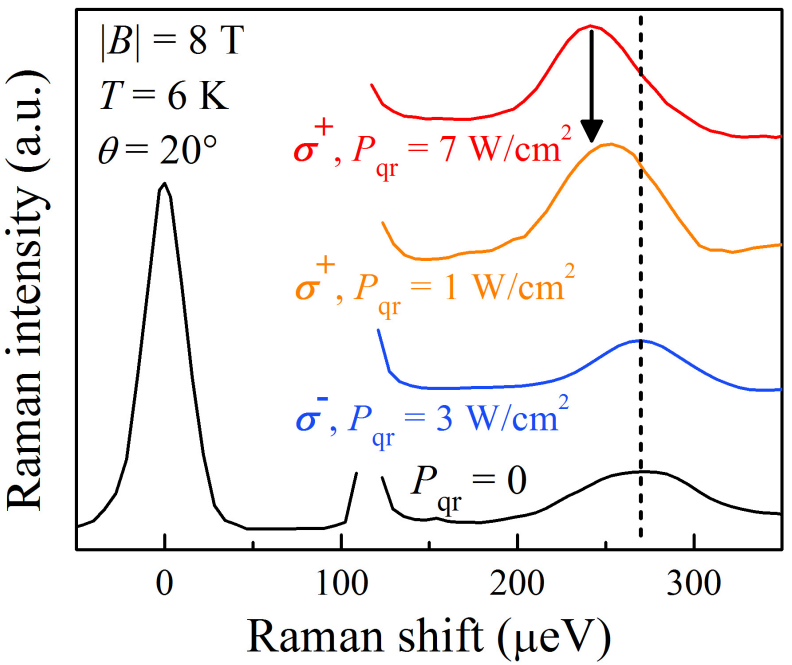
- Determination of $\Gamma$-X mixing and fine structure of indirect exciton

→ (In,Al)As/AlAs QD ensemble is a promising candidate for spintronic applications

## Outlook:

### SFRS sensitive to electron-nuclear hyperfine interaction

- (i) Resonant excitation of QDs at 1.40 eV and in $z(\sigma^+, \sigma^-)\bar{z}$ polarization
- (ii) Quasi-resonant excitation at 1.54 eV (GaAs layer)




$\sigma^+$ excitation: $\Delta E = 252$ μeV

$\sigma^-$ / no pumping: $\Delta E = 269$ μeV

→ $\hat{H} = g_e \mu_B (B + B_N)$

- Overhauser shift increases (by 10 μeV) with increasing $\sigma^+$ pumping power
- Nuclear spin polarization: up to 18%