# Spin scattering in nonmagnetic semiconductors

# Spin state

Wave function: $\left|\psi(\mathbf{k},s)\right\rangle = \varphi_{\uparrow}\left|\mathbf{k},\uparrow\right\rangle + \varphi_{\downarrow}\left|\mathbf{k},\downarrow\right\rangle$

In general, it should be

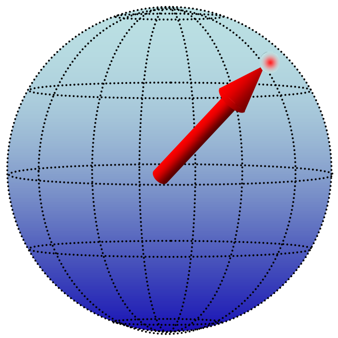
$\rho(\mathbf{k},\mathbf{k}';s,s')$

Use Wigner's function to get

$\rho(\mathbf{K},\mathbf{R};s,s')$

Spin density matrix: $\rho = \left|\psi(\mathbf{k},s)\right\rangle\left\langle\psi(\mathbf{k},s)\right| = \begin{pmatrix} \rho_{\uparrow\uparrow} & \rho_{\uparrow\downarrow} \\ \rho_{\downarrow\uparrow} & \rho_{\downarrow\downarrow} \end{pmatrix}$

OR



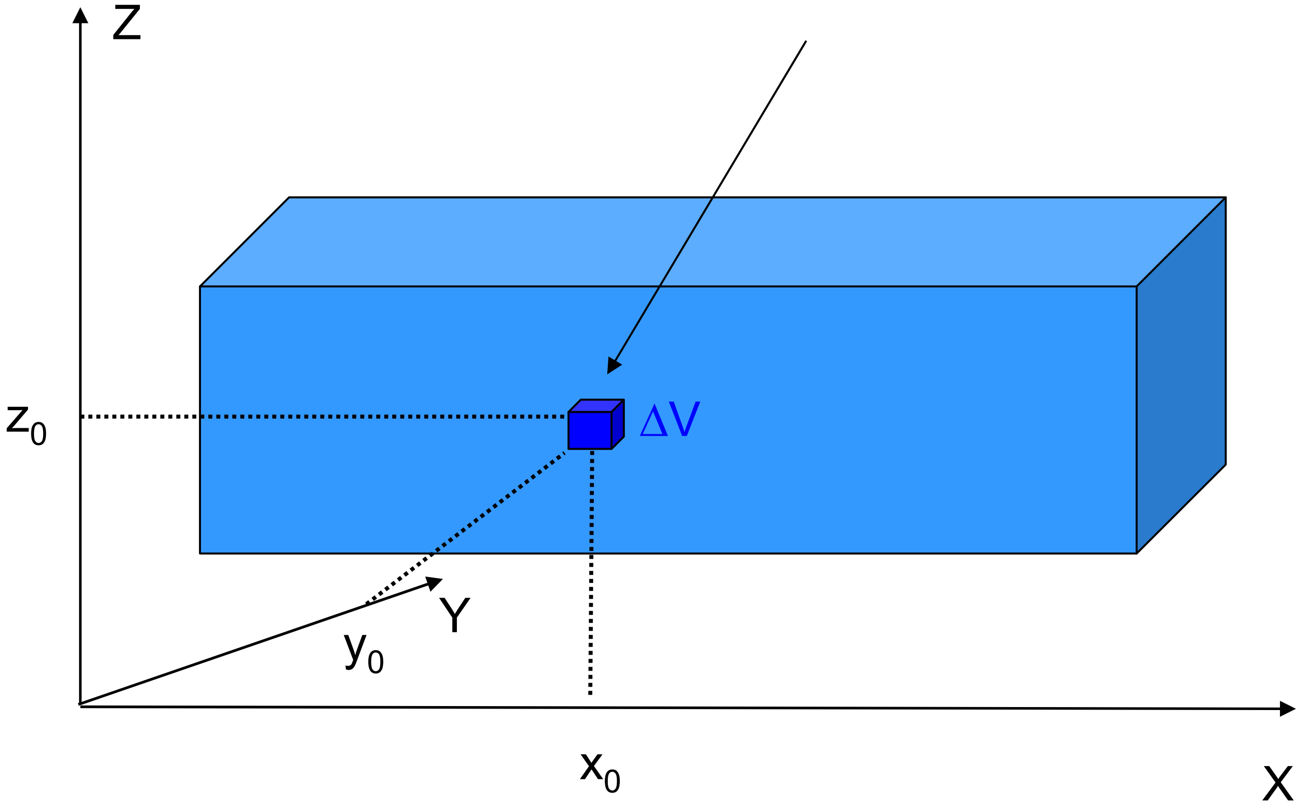
Spin polarization vector: $\vec{P} = \left(P_x, P_y, P_z\right)$

$$\rho_s = \frac{1}{2}\begin{pmatrix} 1+P_z & P_x - iP_y \\ P_x + iP_y & 1-P_z \end{pmatrix}$$

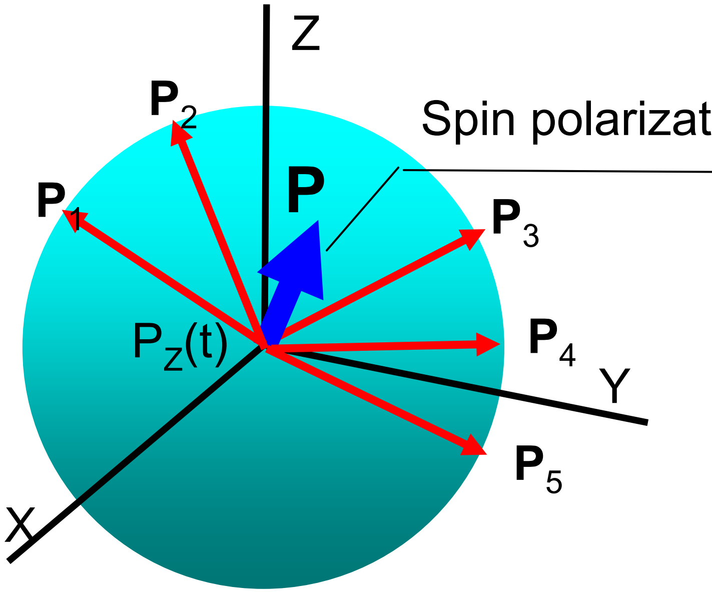
# Local spin polarization

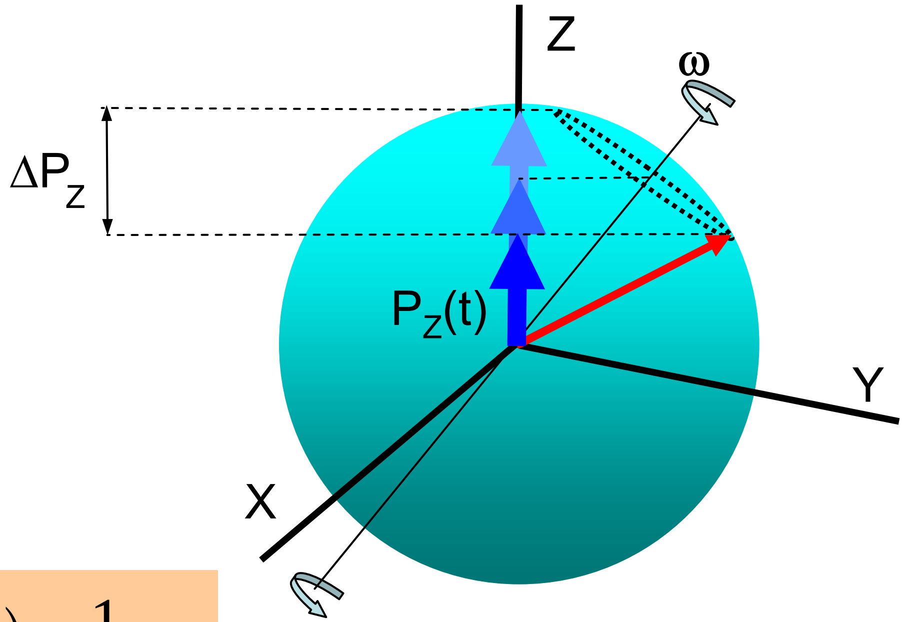
Number of electrons: N=n · ΔV

Magnetic moment: **M**=N·$\mu_B$·**P**



# Spin polarization vector




Bloch equation:

$$\frac{d\vec{P}}{dt} = \gamma \vec{P} \times \vec{B} - \frac{1}{T_1}\left(\vec{P}_{\parallel} - \vec{P}_0\right) - \frac{1}{T_2}\vec{P}_{\perp}$$

**Spin scattering is here**

**Today we talk about $T_1$ processes**

# Evolution of spin polarization vector

## *Interaction with magnetic field*

$$H = -\boldsymbol{\mu}\mathbf{H} = g\mu_B \mathbf{S}\mathbf{H}$$

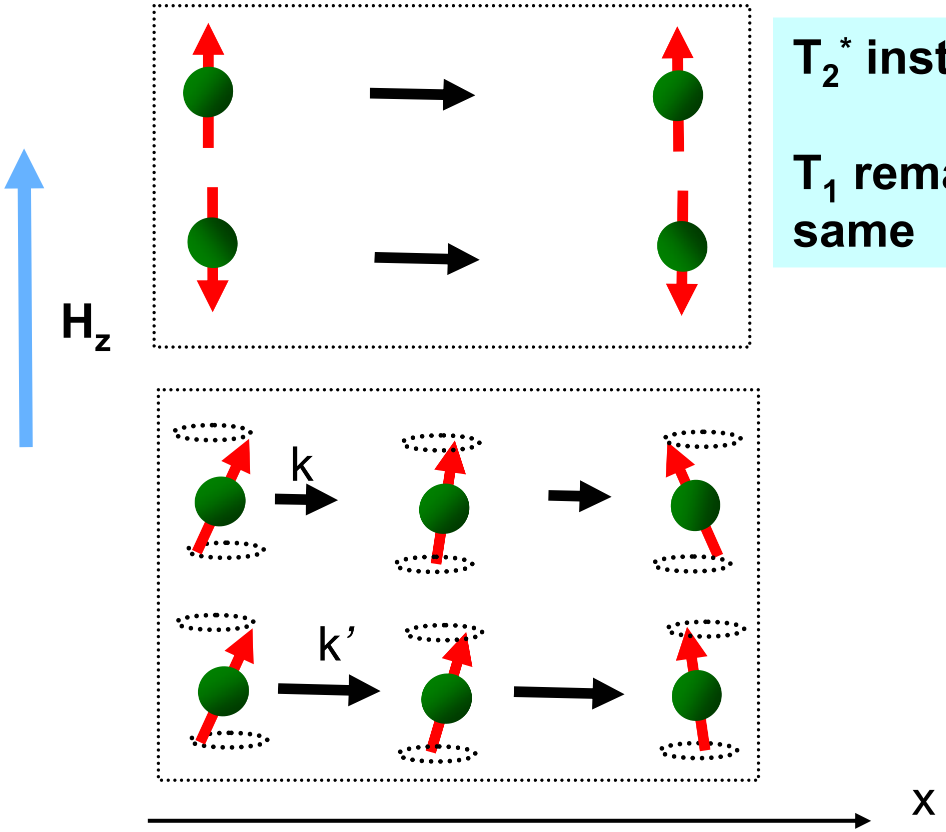
$$\mu_B = 9.27\times 10^{-24} \text{ J/T}$$

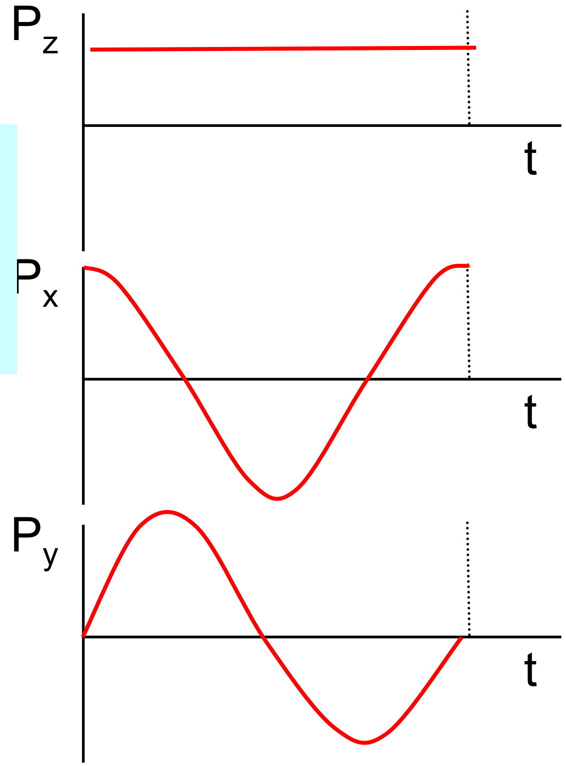
**No scattering!**
**Pure dephasing.**

⇓

**$T_2^*$ instead of $T_2$**

**$T_1$ remains the same**



# Spin scattering

**$T_1$ processes**

We have to define basis for spin ↑ and ↓.
Use small magnetic field.

Spin-orbit interaction

- Elliot-Yafet mechanism
- D'yakonov-Perel mechanism

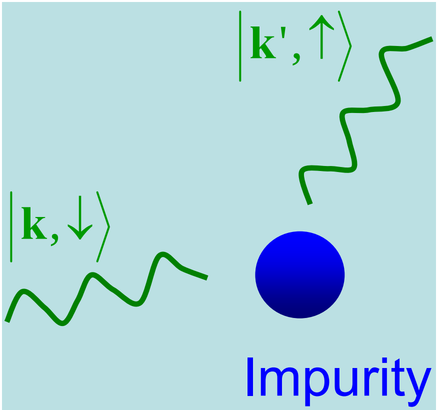
Hyperfine interaction with nuclear spins

Exchange with holes (Bir-Aronov-Pikus)

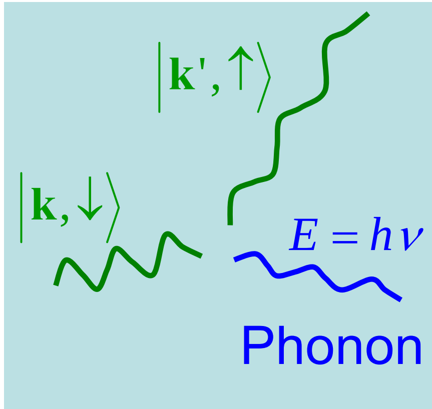
**No direct interaction with phonons & non-magnetic impurities.**

# Spin flip vs. spin precession

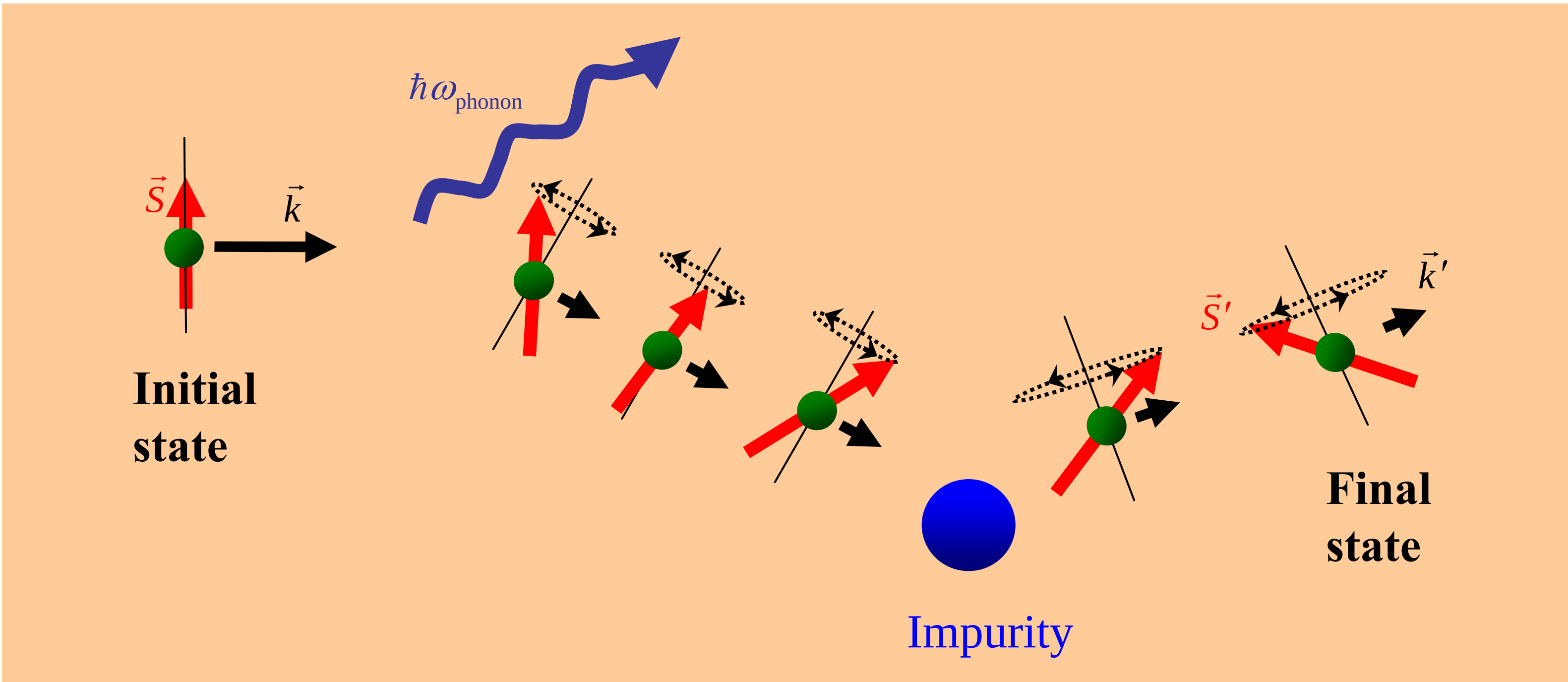
**Type I**




**OR**



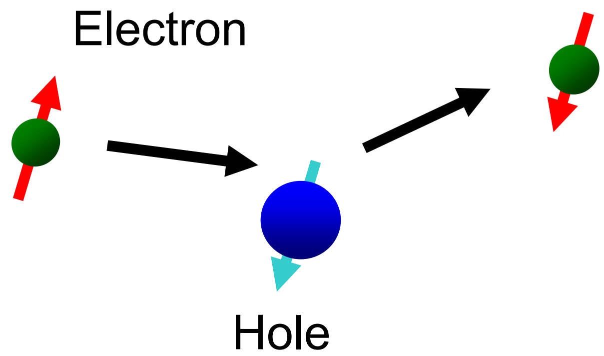

**Type II**



# Electron-hole exchange

Important in p-type semiconductors

Exchange Hamiltonian: $H_{exch} = A\mathbf{J}\mathbf{S}\delta(\mathbf{r})$

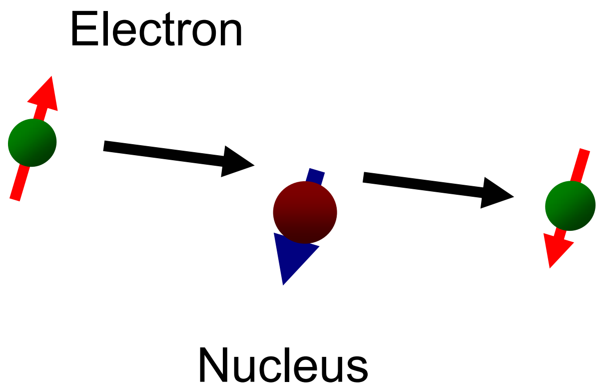



momentum and J can relax

# Hyperfine interaction

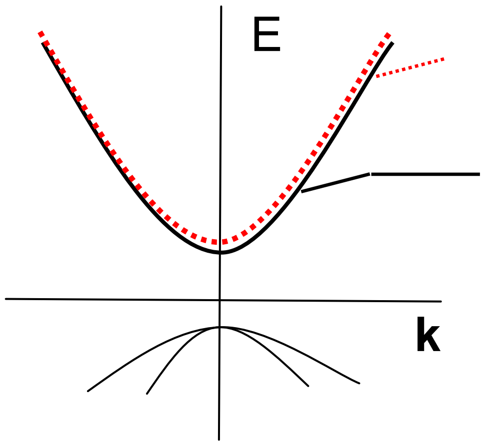
Hyperfine Hamiltonian: $H_{\mathrm{Hf}}(\mathbf{r}) = A\mathbf{S}\mathbf{I}\delta(\mathbf{r})$

Suppressed in strong magnetic fields



# Elliott-Yafet mechanism

Spin states: $\left|\mathbf{k},\downarrow\right\rangle$ $\left|\mathbf{k},\uparrow\right\rangle$

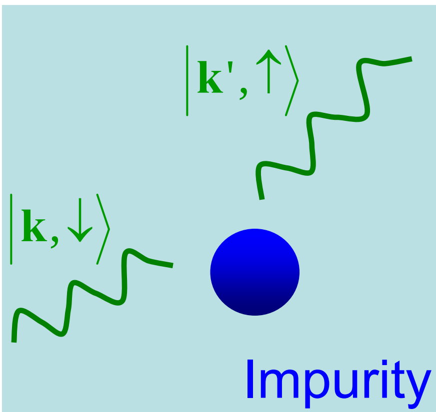


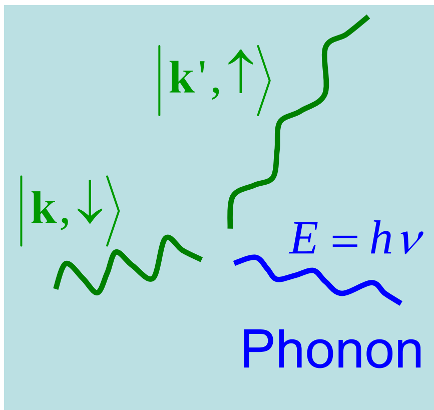

mixes pure spin up and down states

$$\left|k,"\uparrow"\right\rangle = L^{-3/2}e^{i\mathbf{kr}}\left(u_{\mathbf{k}}(\mathbf{r})\left|\uparrow\right\rangle + v_{\mathbf{k}}(\mathbf{r})\left|\downarrow\right\rangle\right)$$

$$\left|k,"\downarrow"\right\rangle = L^{-3/2}e^{i\mathbf{kr}}\left(u'_{\mathbf{k}}(\mathbf{r})\left|\downarrow\right\rangle + v'_{\mathbf{k}}(\mathbf{r})\left|\uparrow\right\rangle\right)$$

**Any momentum scattering can result in a spin flip.**



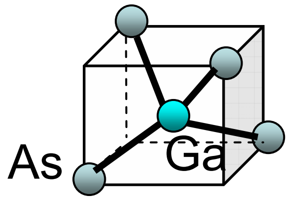



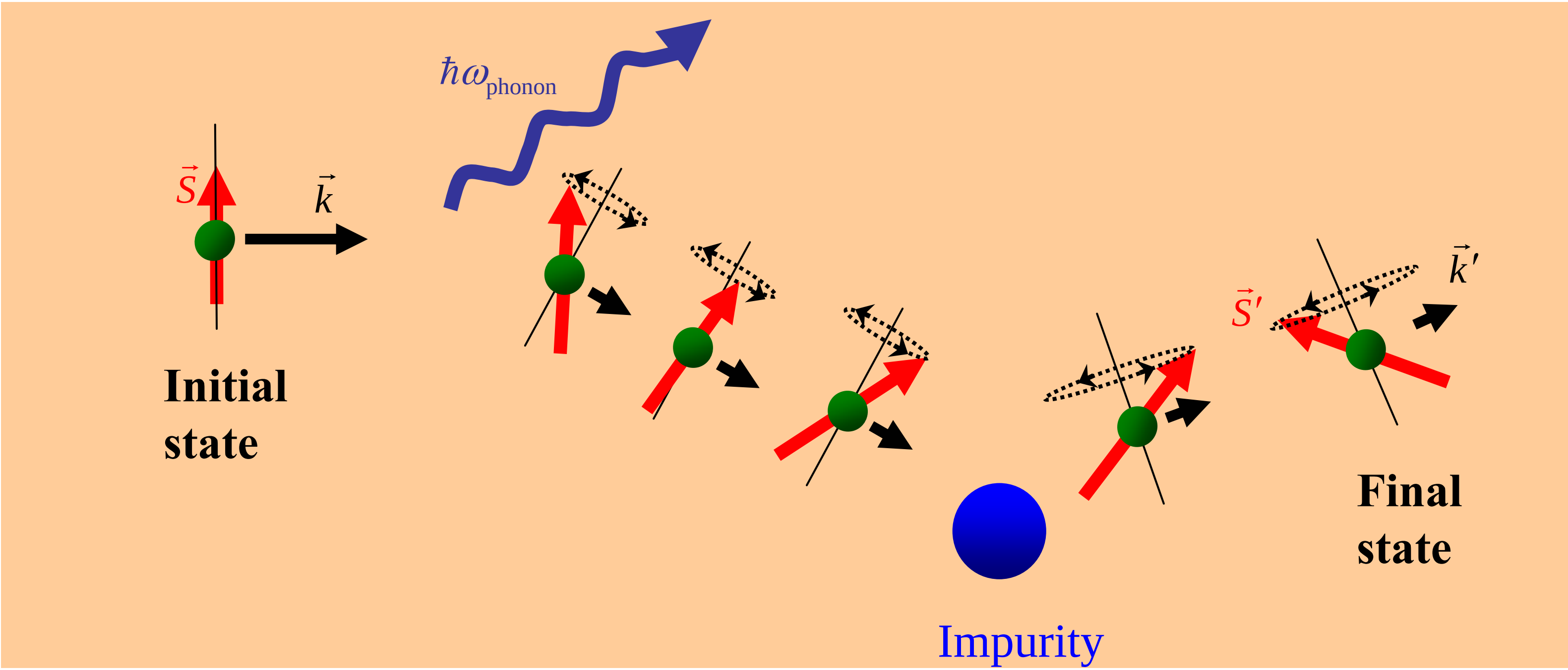
# D'yakonov-Perel' mechanism

Spin-orbit interaction:

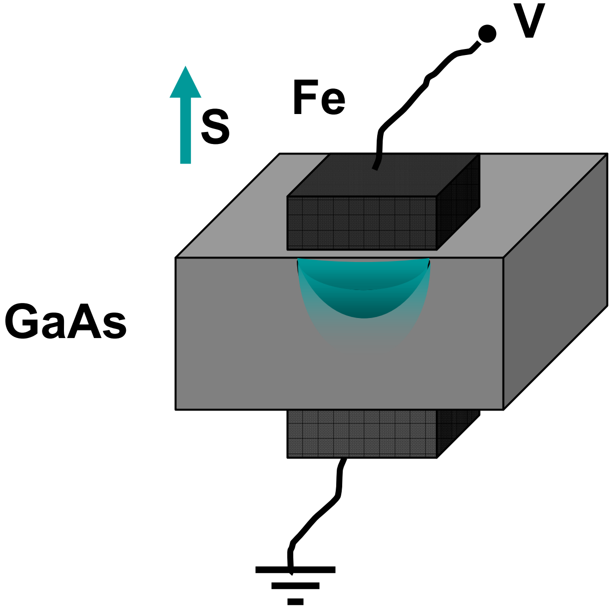
$$H_{SO} = \alpha_\Gamma \left\{ \sigma_x k_x (k_y^2 - k_z^2) + \sigma_y k_y (k_z^2 - k_x^2) + \sigma_z k_z (k_x^2 - k_y^2) \right\}$$

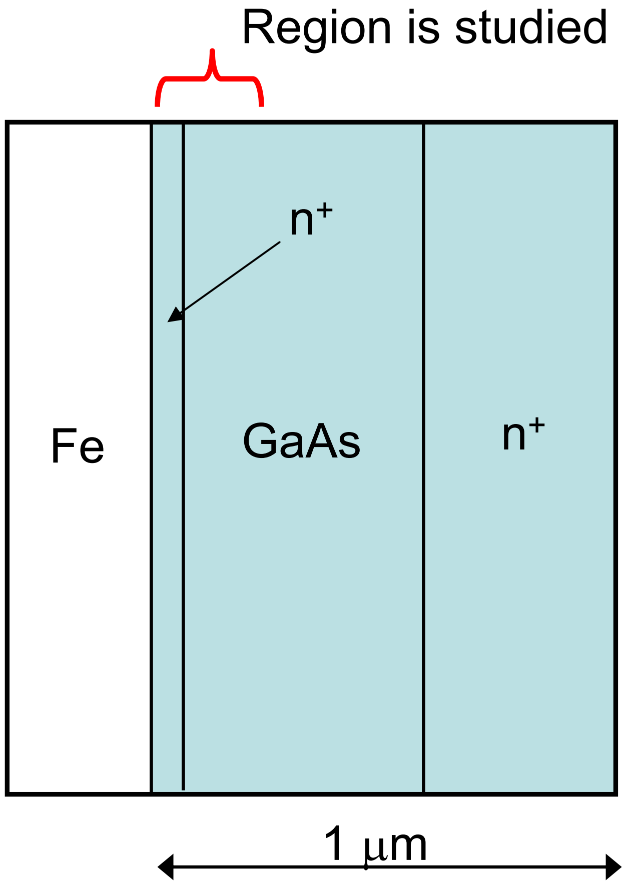
Crystals without a center of inversion



# D-P scattering in a device structure, example



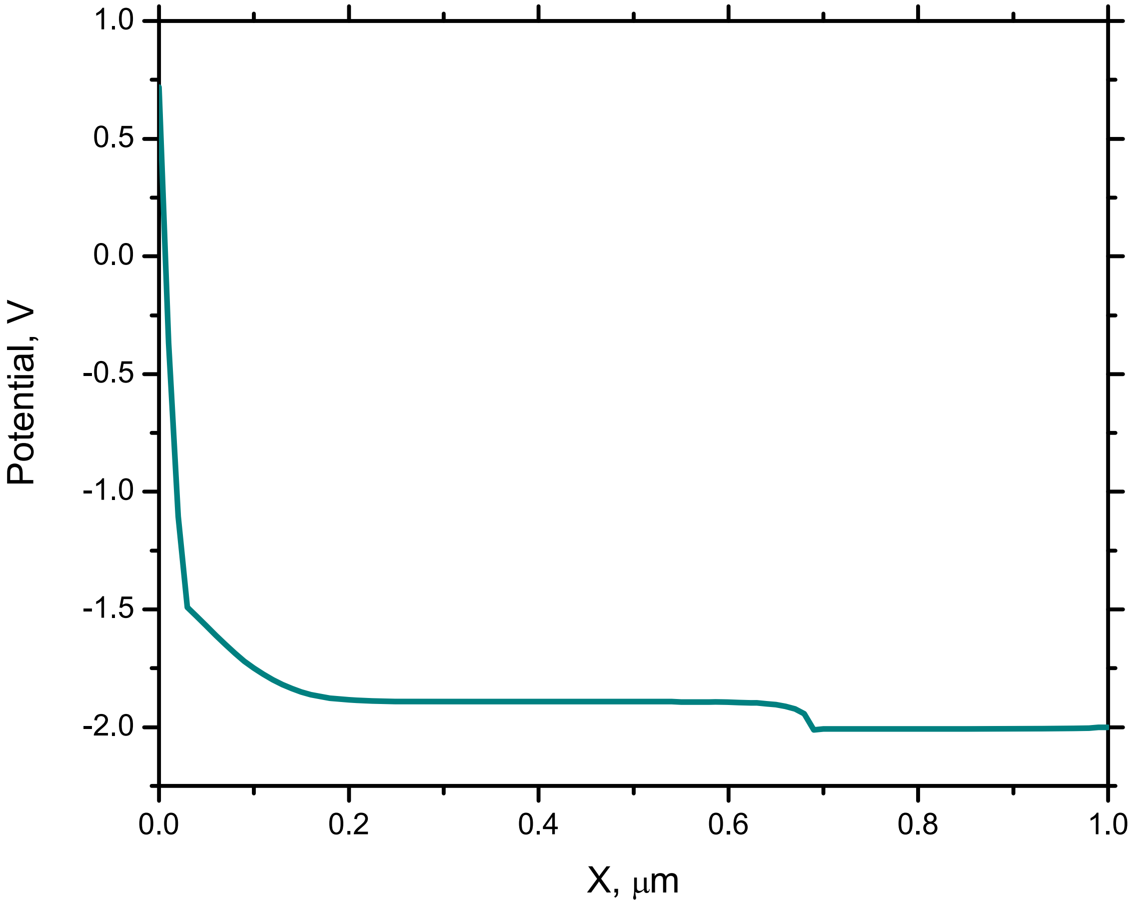

$$q\phi_B = 0.72\ eV$$

$$\alpha_\Gamma = 28\ eVA^3$$

$$\alpha_L = 0.27\ eVA$$

$$\alpha_X = 0.087\ eVA$$

## Potential Profile, Vds = 2 V



# Model for Monte-Carlo simulation

- Charge transport (BTE):

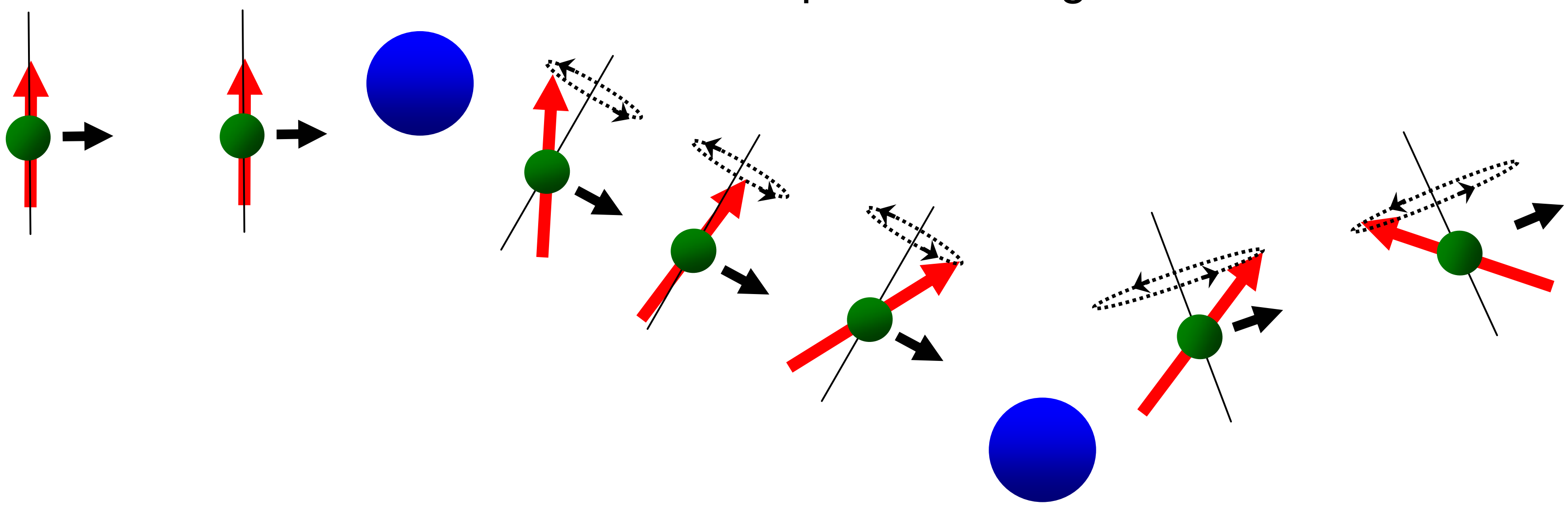
$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \nabla f - \frac{q}{\hbar}(\nabla V) \cdot \nabla_{\mathbf{k}} f = \left( \frac{\partial f}{\partial t} \right)_C$$

$$\nabla^2 V = -\frac{e^2}{\varepsilon_{\mathrm{s}}} \left( n(\mathbf{r}) - N_{\mathrm{d}} \right)$$

- Spin density matrix evolution:

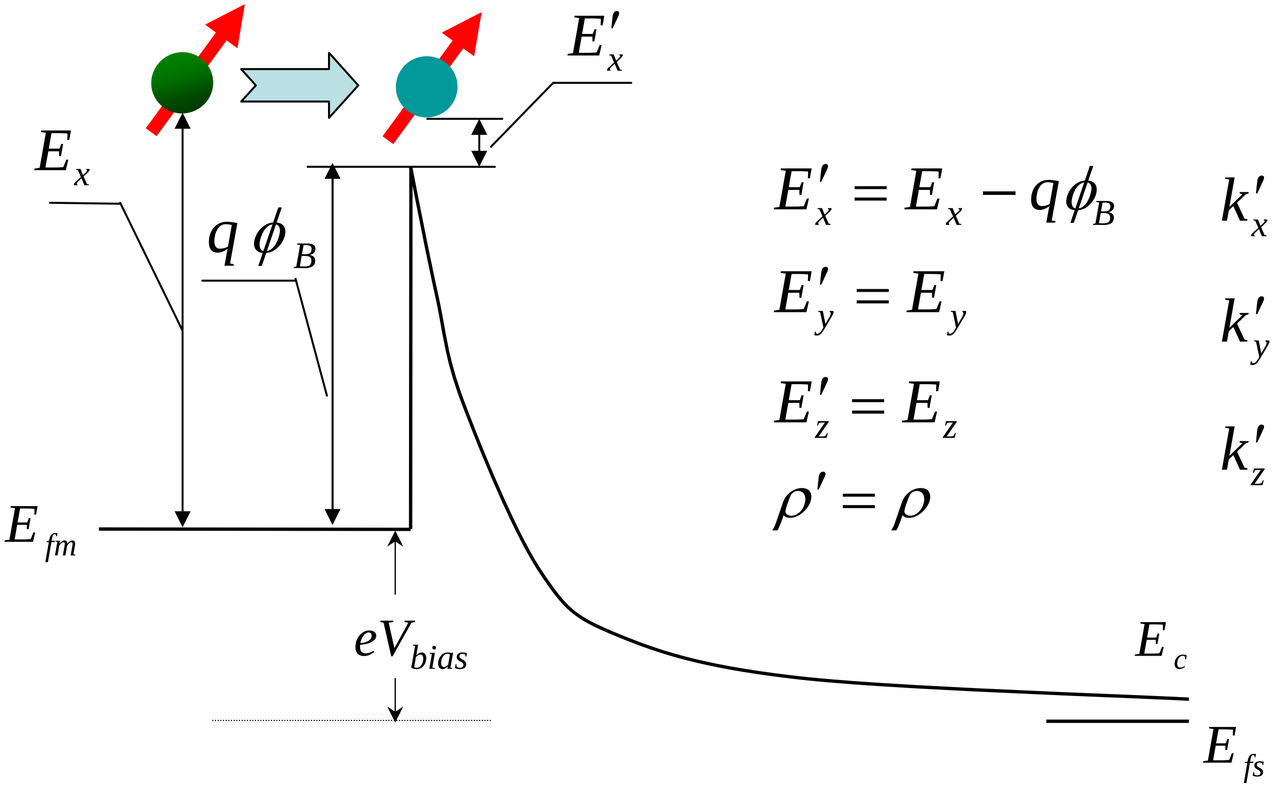
$$\rho_i(t + dt) = e^{-iH_{\mathrm{SO}} dt/\hbar} \rho_i(t) e^{iH_{\mathrm{SO}} dt/\hbar}$$

- Spin scattering mechanism:



# Injection Mechanisms

- **Thermionic Emission:** $E_x > q\phi_B$ & spin is conserved




$$E'_x = E_x - q\phi_B \qquad k'_x = \sqrt{2m^* E'_x}/\hbar$$

$$E'_y = E_y \qquad k'_y = \pm\sqrt{2m^* E'_y}/\hbar$$

$$E'_z = E_z \qquad k'_z = \pm\sqrt{2m^* E'_z}/\hbar$$

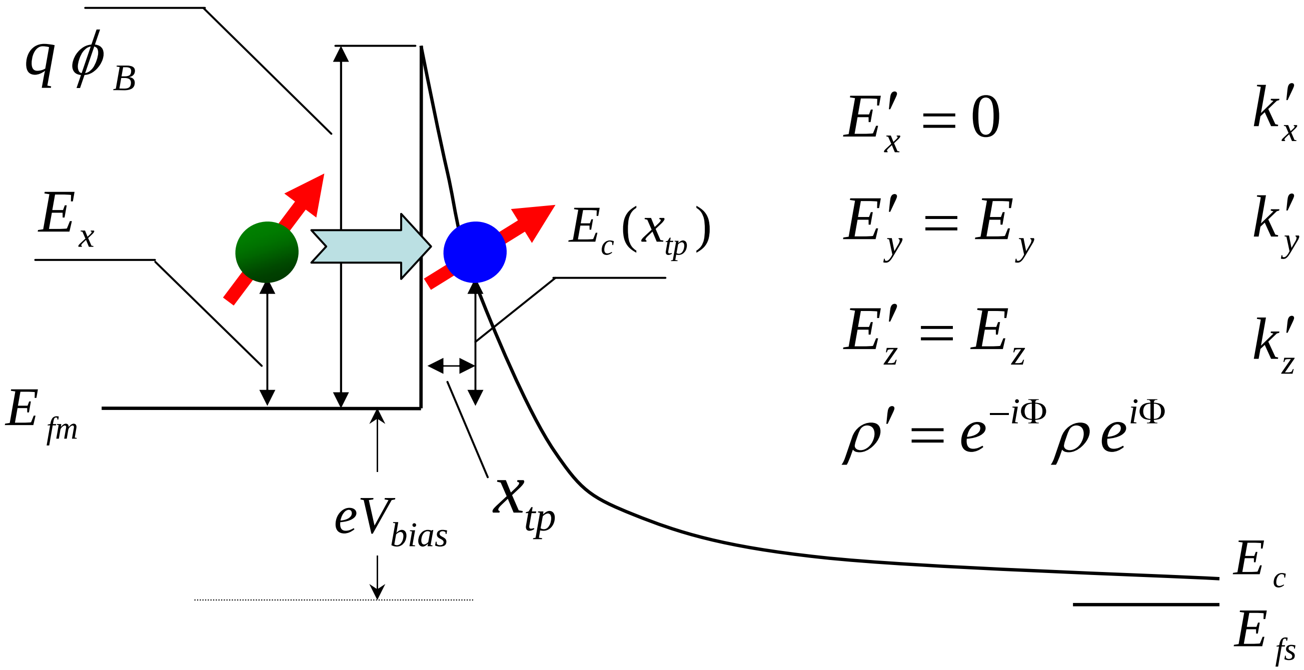
$$\rho' = \rho$$

# Injection Mechanisms

- **Tunneling through the Schottky barrier:** $E_x < q\phi_B$

Tunneling probability:
(WKB approximation)

$$T_{\mathrm{tp}}(E) = \exp\left(-\frac{2}{\hbar}\int_0^{x_{tp}} \sqrt{2m^*[E_c(x) - E_x]}\, dx\right)$$




$$E'_x = 0 \qquad k'_x = 0$$

$$E'_y = E_y \qquad k'_y = \pm\sqrt{2m^* E'_y}\,/\,\hbar$$

$$E'_z = E_z \qquad k'_z = \pm\sqrt{2m^* E'_z}\,/\,\hbar$$

$$\rho' = e^{-i\Phi}\rho\, e^{i\Phi}$$

# Electrons at the Ferromagnetic Contact

- Electron distribution function:

$$f(E) = \frac{1}{1 + e^{(E - E_{fm})/k_B T}} \sim e^{-(E - E_{fm})/k_B T}$$

- Equal average kinetic energy in *x*, *y* and *z* directions

- Probabilities of spin states are based on the densities of states

$$P_{\uparrow}(E) = \frac{D_{\uparrow}(E)}{D_{\uparrow}(E) + D_{\downarrow}(E)} \quad \text{and} \quad P_{\downarrow} = 1 - P_{\uparrow}$$

# Spin-orbit couplings in 3 valleys of bulk GaAs

## *Dresselhaus Mechanism*

1. **Γ valley (000)**

$$H_{SO} = \alpha_\Gamma \left\{ \sigma_x k_x (k_y^2 - k_z^2) + \sigma_y k_y (k_z^2 - k_x^2) + \sigma_z k_z (k_x^2 - k_y^2) \right\}$$

2. **L valleys**

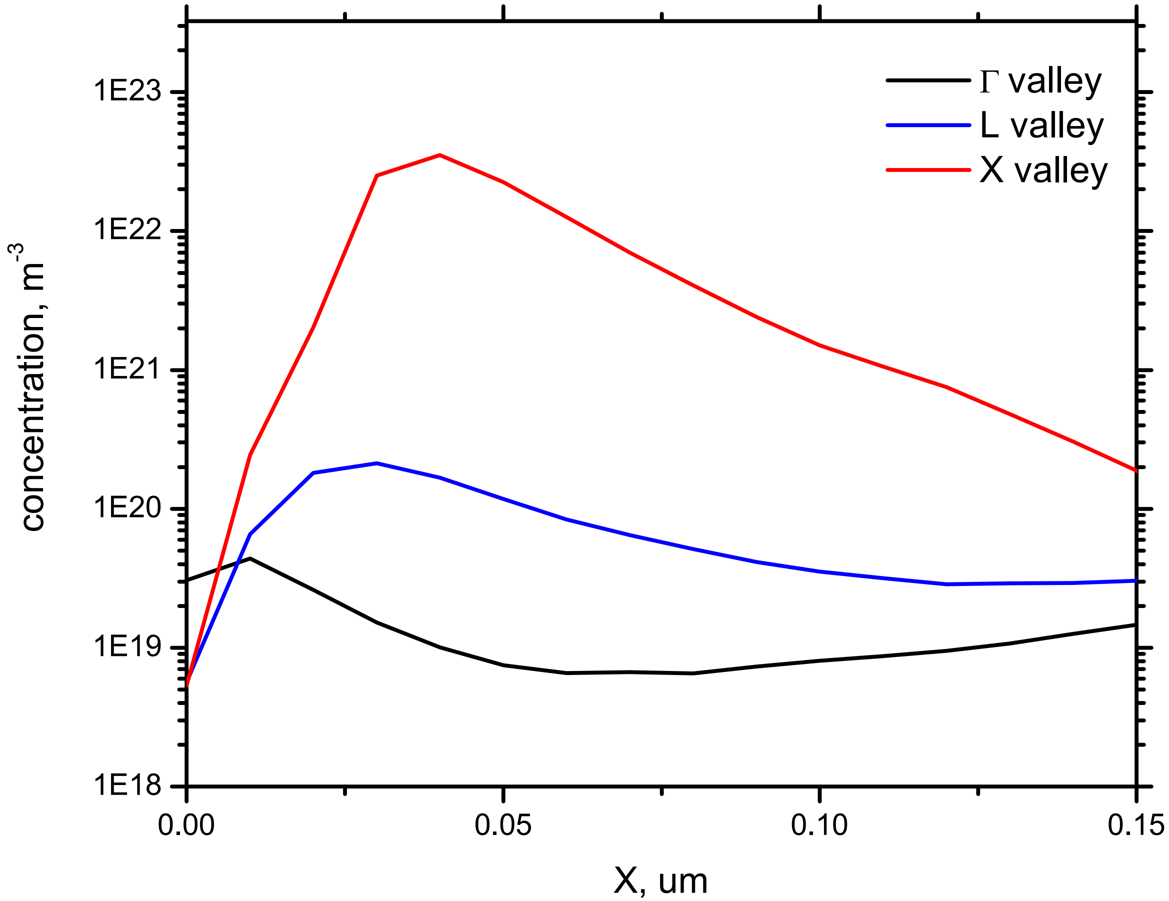
$$H_{SO} = \begin{cases} \alpha_L / \sqrt{3} \left\{ \sigma_x (k_y - k_z) + \sigma_y (k_z - k_x) + \sigma_z (k_x - k_y) \right\} & (\ 1\ 1\ 1) \\ \alpha_L / \sqrt{3} \left\{ \sigma_x (k_y + k_z) - \sigma_y (k_x + k_z) + \sigma_z (k_y - k_x) \right\} & (-1 -1\ 1) \\ \alpha_L / \sqrt{3} \left\{ \sigma_x (-k_y - k_z) + \sigma_y (k_x - k_z) + \sigma_z (k_x + k_y) \right\} & (-1\ 1 -1) \\ \alpha_L / \sqrt{3} \left\{ \sigma_x (k_z - k_y) + \sigma_y (k_x + k_z) - \sigma_z (k_x + k_y) \right\} & (1 -1\ -1) \end{cases}$$

3. **X valleys**

$$H_{SO} = \begin{cases} \alpha_X (\sigma_z k_z - \sigma_y k_y) & (\pm 1\ 1\ 1) \\ \alpha_X (\sigma_x k_x - \sigma_z k_z) & (\ 1 \pm 1\ 1) \\ \alpha_X (\sigma_x k_x - \sigma_y k_y) & (\ 1\ 1 \pm 1) \end{cases}$$

# Carrier Concentration

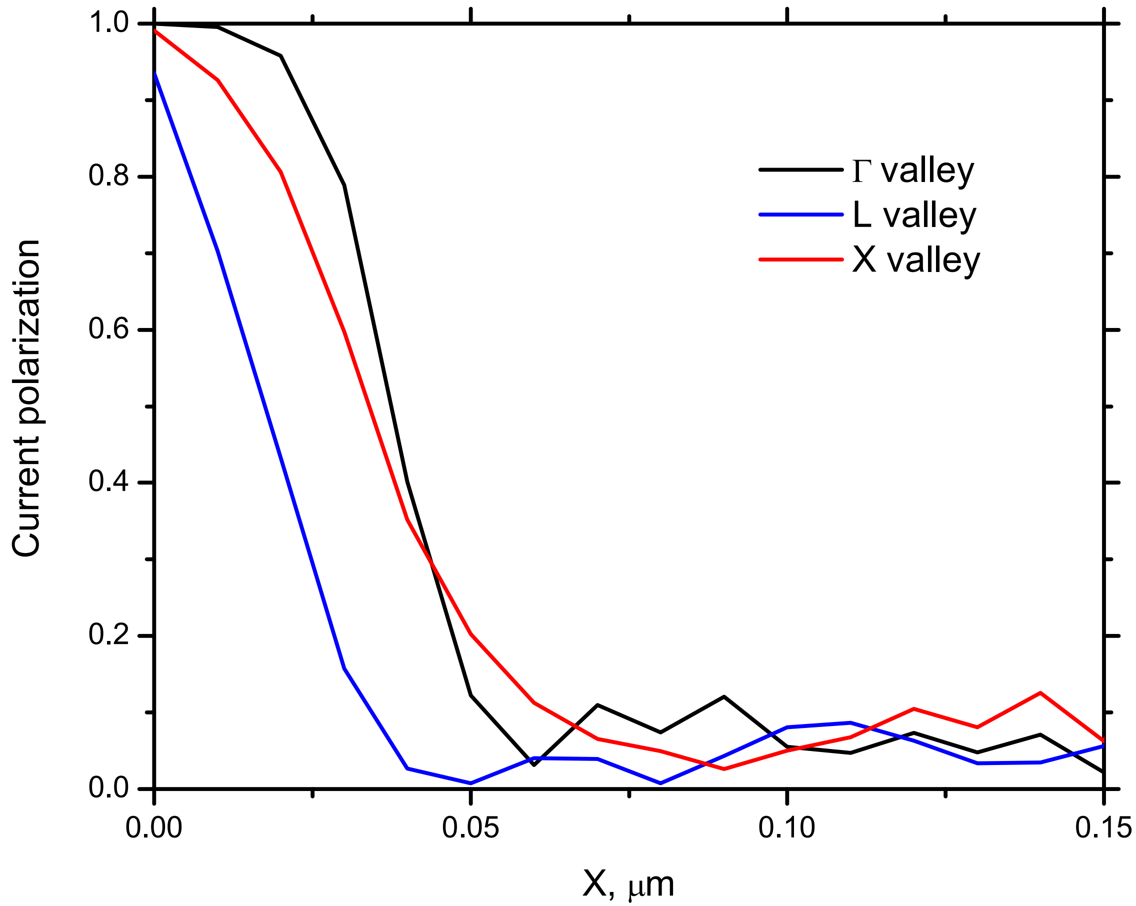
***T* = 300 K, *V* = 2 V**




The extremely high electric field at the Schottky barrier pumps the electrons onto up valleys, especially the X valley

***T* = 300 K, *V* = 2 V**

## Current Spin Polarization

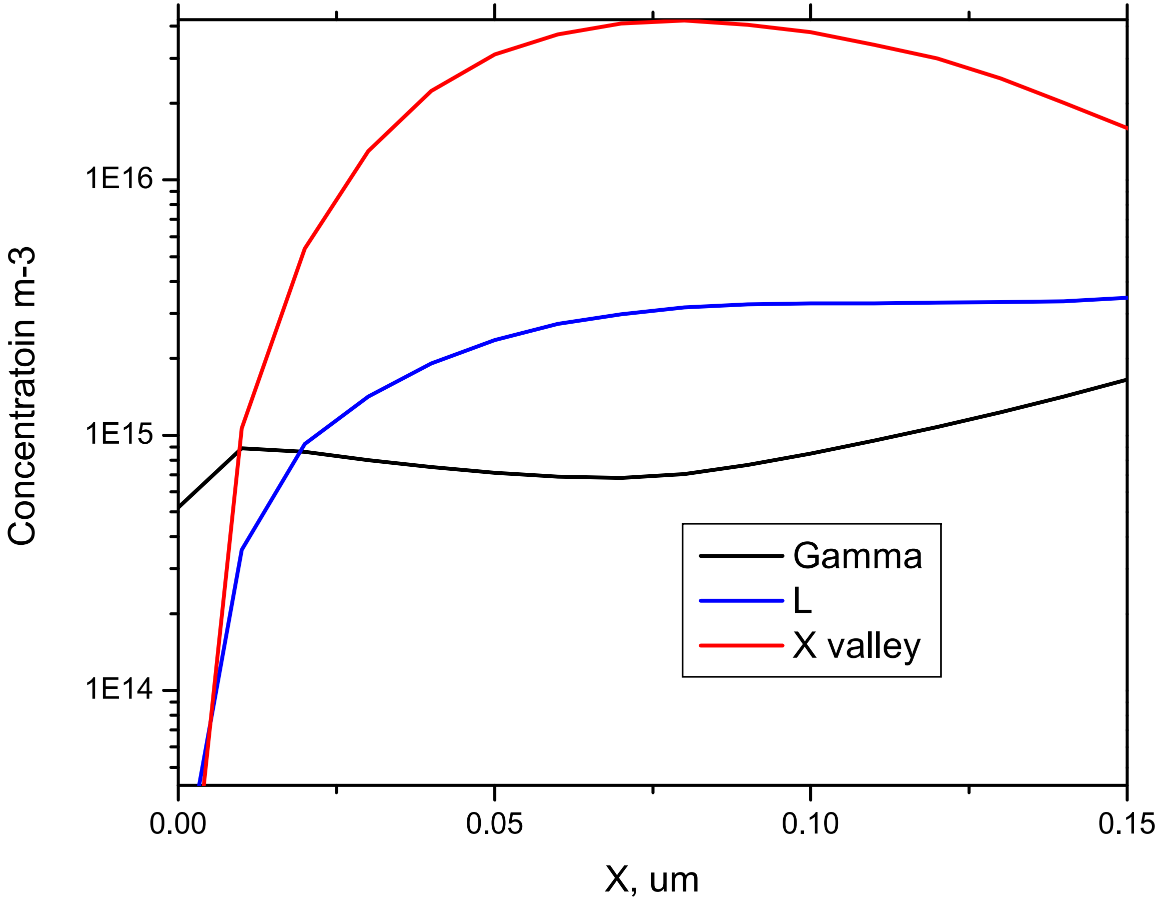



Spin dephasing is much stronger in upper valleys due stronger SO coupling

***T* = 300 K, *V* = 0.5 V**

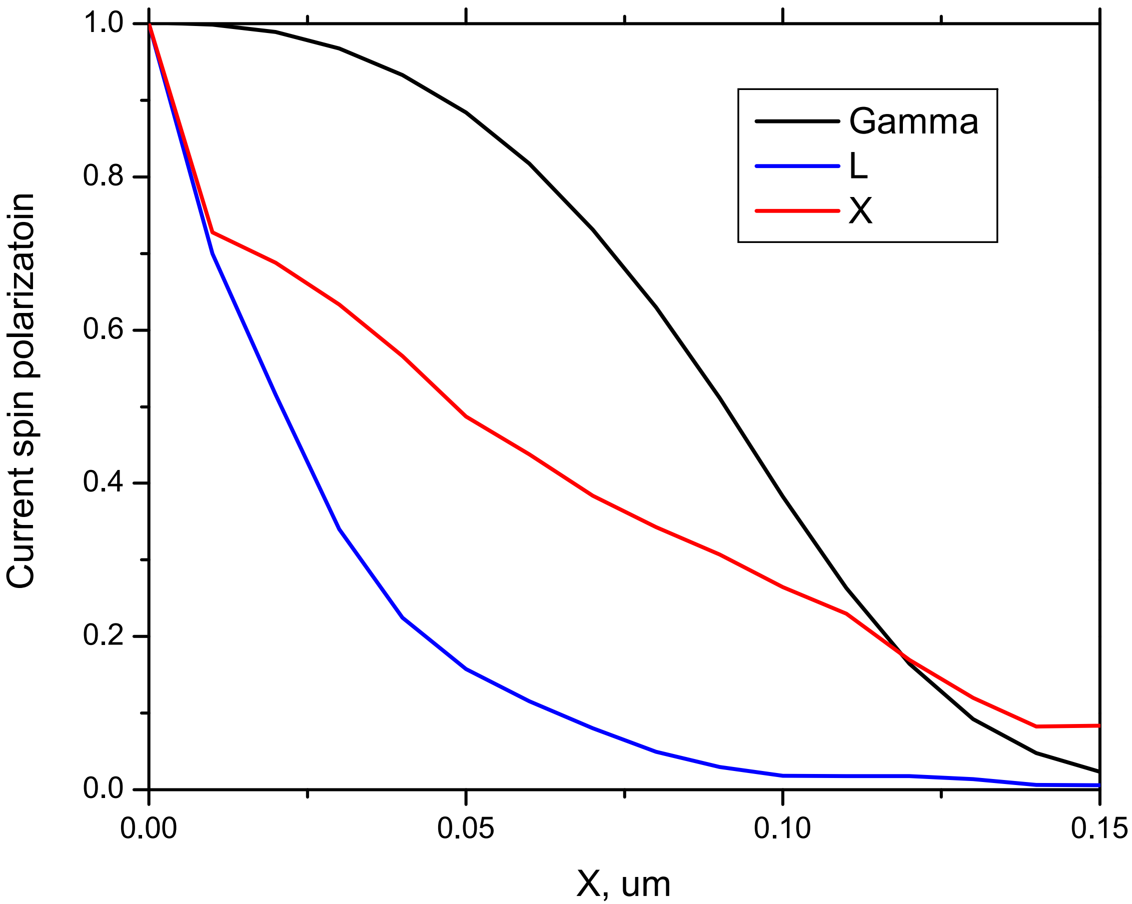
**Low bias**

## Carrier Concentration



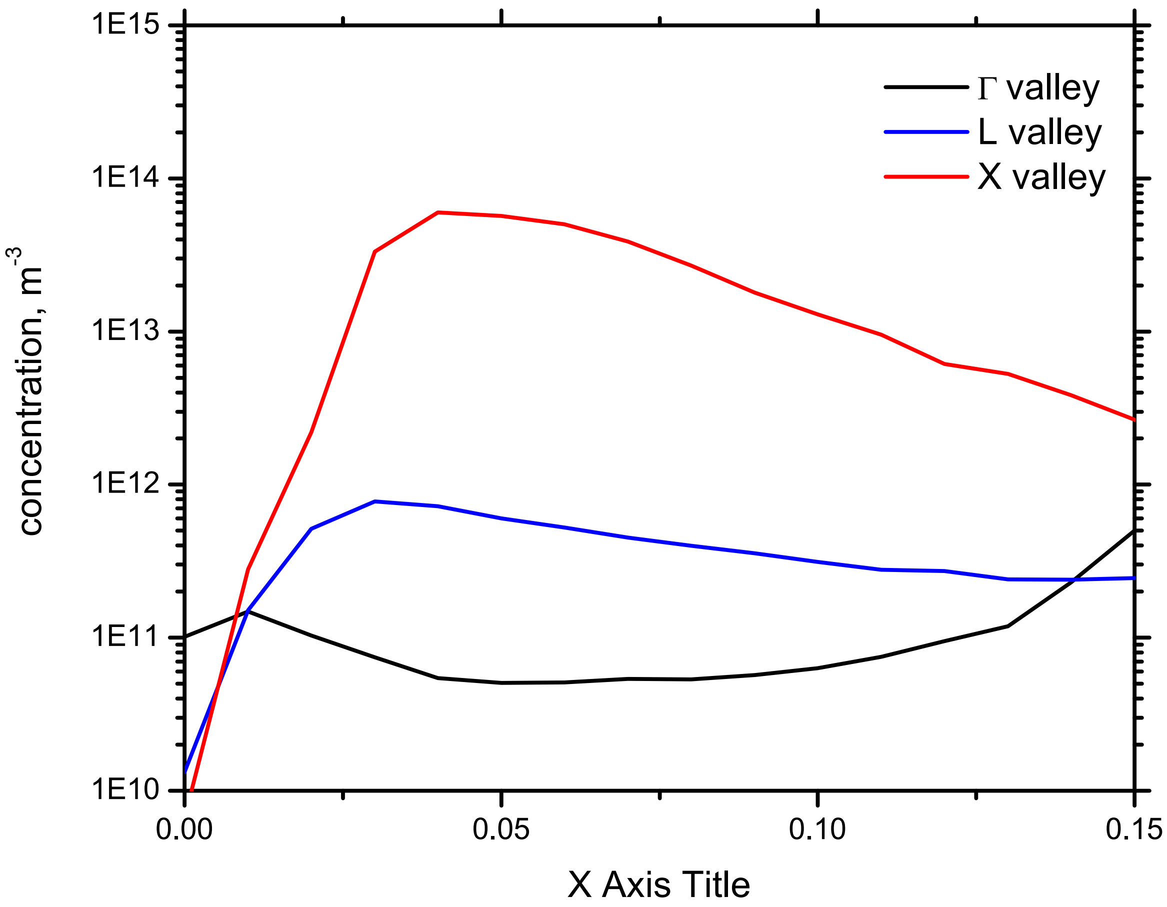
***T* = 300 K, *V* = 0.5 V**

## Current Spin Polarization



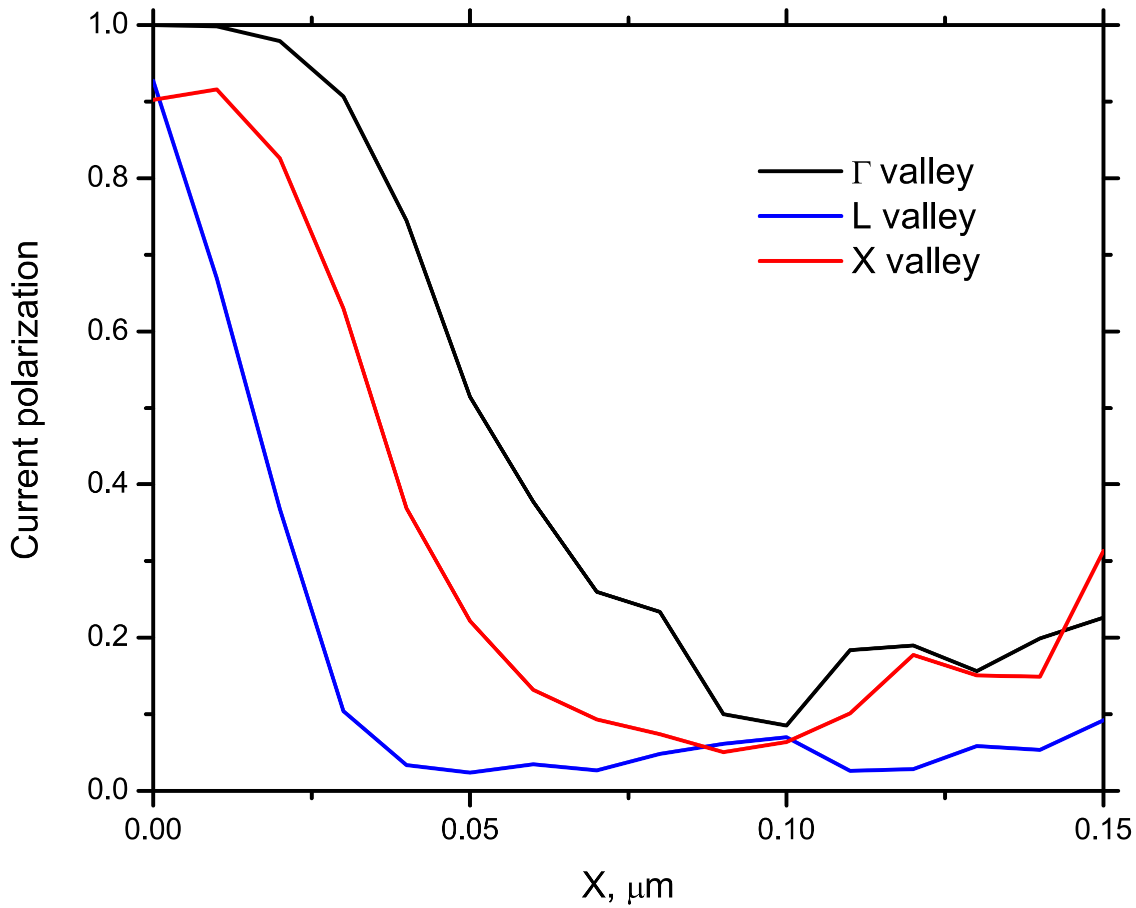
**Low temperature** ***T* = 80 K, *V* = 2 V**

## Carrier Concentration

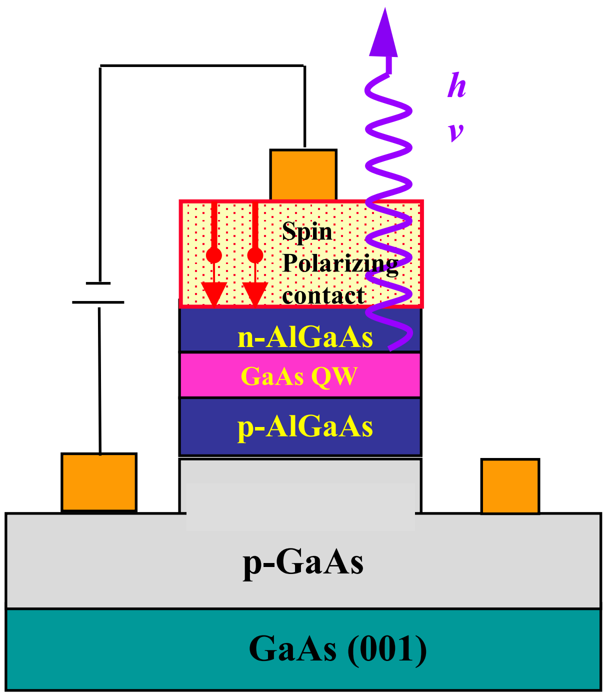


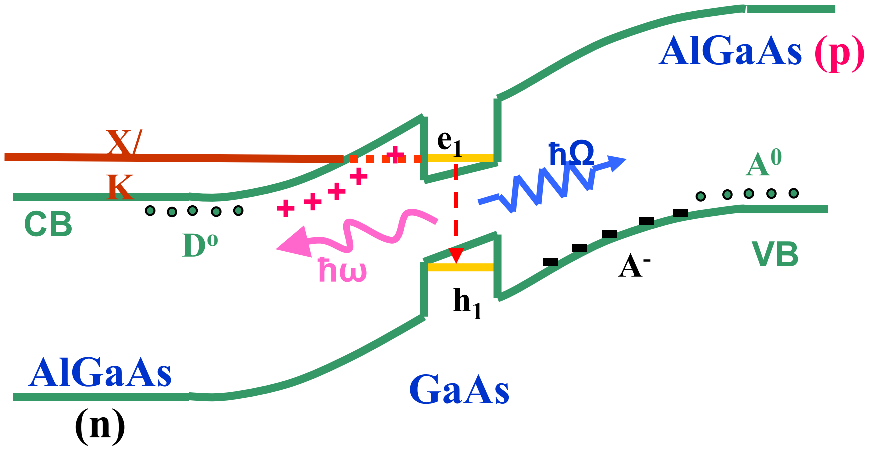
## Low temperature *T* = 80 K, *V* = 2 V

## Current Spin Polarization



# Spin-LED



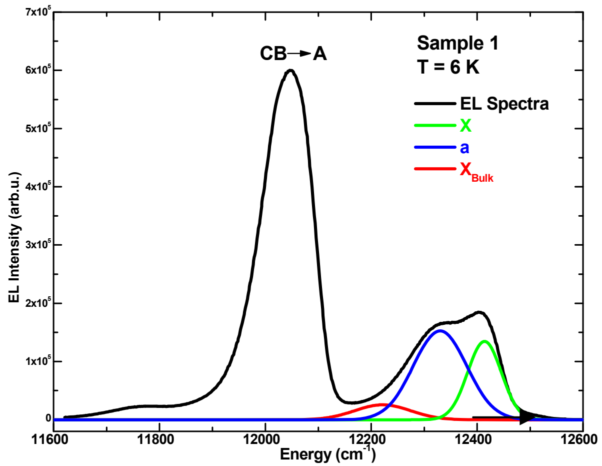



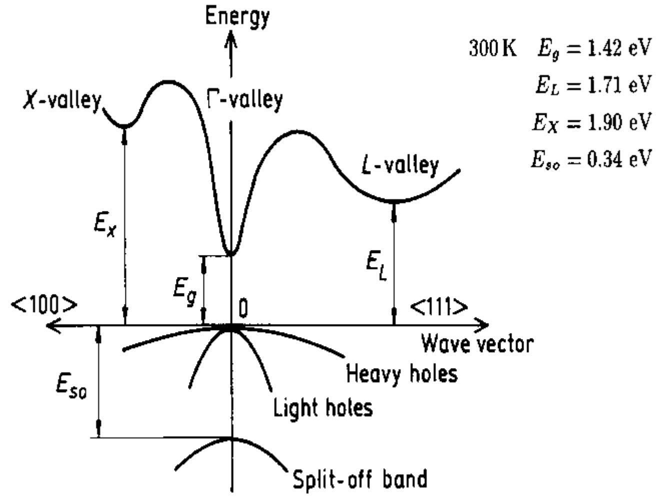

M. Yasar, PhD Thesis

# Spin-LED

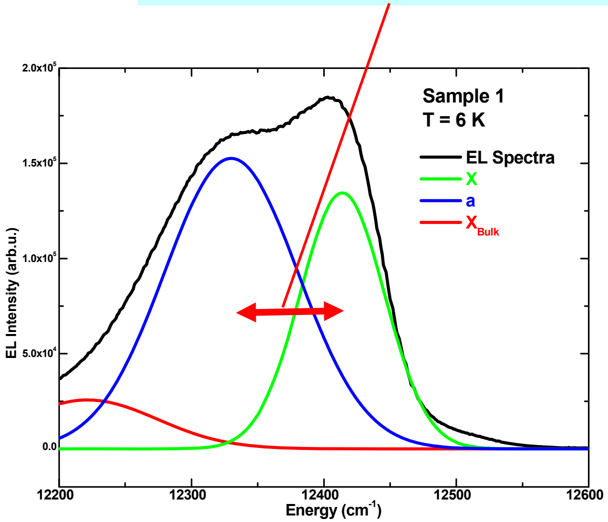
Electroluminescence (1,0,0)

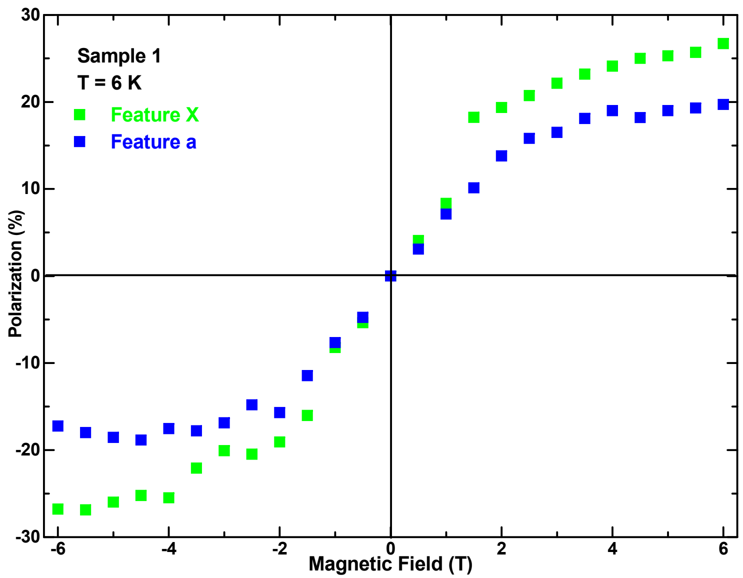
R. Mallory, et. al., Phys. Rev. B 73, 115308 (2006)



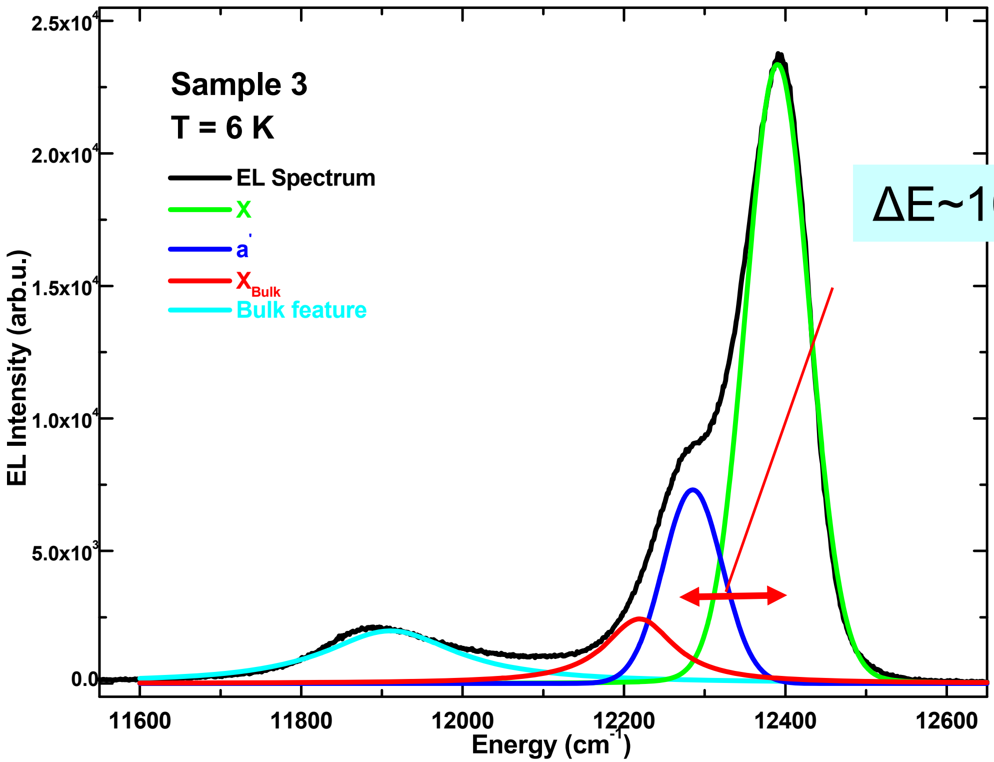

ΔE~84 $cm^{-1}$ = TA phonon at X



# Spin-LED

Electroluminescence (1,1,0)




ΔE~105 $cm^{-1}$ ~ phonon at K

# Questions?