Spin Dynamics in Semiconductors

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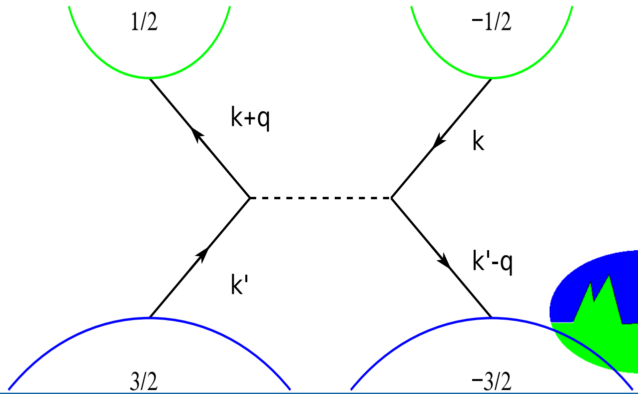
Prof. Dr. T. S. Lai Group *from Zhongshan Univ.*

Outline

- Spin relaxation/dephasing mechanisms
- *Fully microscopic* approach to spin kinetics
- Comparisons with experiments
- Spin kinetics *far away* from equilibrium
  - Spin dephasing at large spin polarization
  - Spin dephasing in the presence of high electric field
- Footprint of the Coulomb scattering in spin relaxation
- Non-Markovian spin kinetics
- Spin dynamics with strong THz fields
- Spin diffusion and transport

Spin Dephasing/Relaxation Mechanisms

- Elliot-Yafet Mechanism [Yafet, PR **85**, 478 (1952); Elliot, PR **96**, 266 (1954)]: *Spin-flip electron-phonon and electron-impurity scattering* $\propto 1/E_g^2$
- DP Mechanism [D'yakonov & Perel', Sov. Phys. JETP **38**, 1053 (1971)]: $[\mu_B g\mathbf{B} + \mathbf{\Omega}(\mathbf{k})] \cdot \frac{\boldsymbol{\sigma}}{2}$ *with*
  - Dresselhaus Term (Bulk Inversion Asymmetry) $\Omega_x(\mathbf{k}) = \gamma k_x(k_y^2 - k_z^2)$, $\Omega_y(\mathbf{k}) = \gamma k_y(k_z^2 - k_x^2)$, *and* $\Omega_z(\mathbf{k}) = \gamma k_z(k_x^2 - k_y^2)$.
  - Rashba Term (Structure Inversion Asymmetry) $\mathbf{\Omega}(\mathbf{k}) = \alpha(\mathbf{k} \times \mathbf{E}) \cdot \boldsymbol{\sigma}$
- BAP Mechanism [Bir *et al.*, Sov. Phys. JETP **42**, 705 (75)]: *Band mixing* + *Coulomb scattering*. *p-type*



Spin Relaxation based on Single-Particle Approach

[Meier and Zakharchenya, *Optical Orientation* (North-Holland, Amsterdam, 1984)]

$$\frac{1}{\tau_{\mathrm{DP}}} = 8Q\gamma_D^2 m_c^3 \left(k_B T\right)^3 \tau_p$$

$$\frac{1}{\tau_{\mathrm{EY}}} = A\left(\frac{k_B T}{E_g}\right)^2 \eta^2 \left(\frac{1-\eta/2}{1-\eta/3}\right)^2 \frac{1}{\tau_p}$$

For non-degenerate holes: $$\frac{1}{\tau_{\mathrm{BAP}}} = \frac{2}{\tau_0} n_h a_B^3 \frac{\langle v_{\mathbf{k}} \rangle}{v_B}$$

For degenerate holes: $$\frac{1}{\tau_{\mathrm{BAP}}} = \frac{3}{\tau_0} n_h a_B^3 \frac{\langle v_{\mathbf{k}} \rangle}{v_B} \frac{k_B T}{E_{Fh}}$$

Problems of Single-Particle Approach

- Based on elastic scattering approximation

  Incorrect at some low impurity density cases [Weng and Wu, PRB **68**, 075312 (03)]

- Without carrier-carrier Coulomb scattering, Coulomb Hartree-Fock term and Pauli blocking

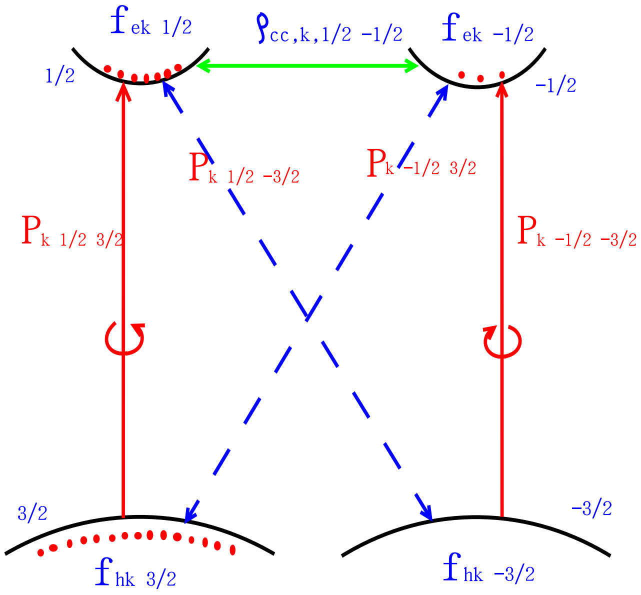
  These are proved to be important and accepted by the community [Weng and Wu, PRB **68**, 075312 (03); Zhou, Cheng, and Wu, PRB **75**, 045305 (07); Zhou and Wu, PRB **77**, 075318 (08); *Spin Physics in Semiconductors*, ed. by D'yakonov (Springer, Berlin, 08)]

- Can not study spin dynamics in system out of motional narrowing regime, in non-Markovian limit, or far away from equilibrium

  These were studied via KSBE approach in [Weng, Wu, and Jiang, PRB **69**, 245320 (04); Lü, Cheng, and Wu, PRB **73**, 125314 (06); Zhang and Wu, PRB **76**, 193312 (07); Zhang, Zhou, and Wu, PRB **77**, 235323 (08); Jiang, Wu, and Zhou, PRB **78**, 125309 (08)]

Kinetic Spin Bloch Approach

[Wu *et al.*, Eur. Phys. J. B **18**, 373 (00); PRB **61**, 2945 (00); **68**, 075312 (03); **69**, 245320 (04)]



$$\frac{\partial\rho(\mathbf{R},\mathbf{k},t)}{\partial t} - \frac{1}{2}\{\nabla_{\mathbf{R}}\bar{\varepsilon}(\mathbf{R},\mathbf{k},t), \nabla_{\mathbf{k}}\rho(\mathbf{R},\mathbf{k},t)\}$$
$$+\frac{1}{2}\{\nabla_{\mathbf{k}}\bar{\varepsilon}(\mathbf{R},\mathbf{k},t), \nabla_{\mathbf{R}}\rho(\mathbf{R},\mathbf{k},t)\}$$
$$= \left.\frac{\partial\rho(\mathbf{R},\mathbf{k},t)}{\partial t}\right|_c + \left.\frac{\partial\rho(\mathbf{R},\mathbf{k},t)}{\partial t}\right|_s .$$

Poisson Eq.: $\nabla^2_{\mathbf{R}}\psi(\mathbf{R},t) = -e\big[n(\mathbf{R},t) - n_0(\mathbf{R})\big]/\epsilon$,

where $\dot{\rho}_{\mathbf{k},\sigma\sigma'}|_{\text{coh}} = -i[(g\mu_B\mathbf{B} + \mathbf{\Omega}(\mathbf{k}))\cdot\frac{\boldsymbol{\sigma}}{2} + \epsilon_{HF}(\mathbf{R},\mathbf{k}), \rho_{\mathbf{k},\sigma\sigma'}]$

Dresselhause/Rashba coupling (Inhomogeneous Broadening):

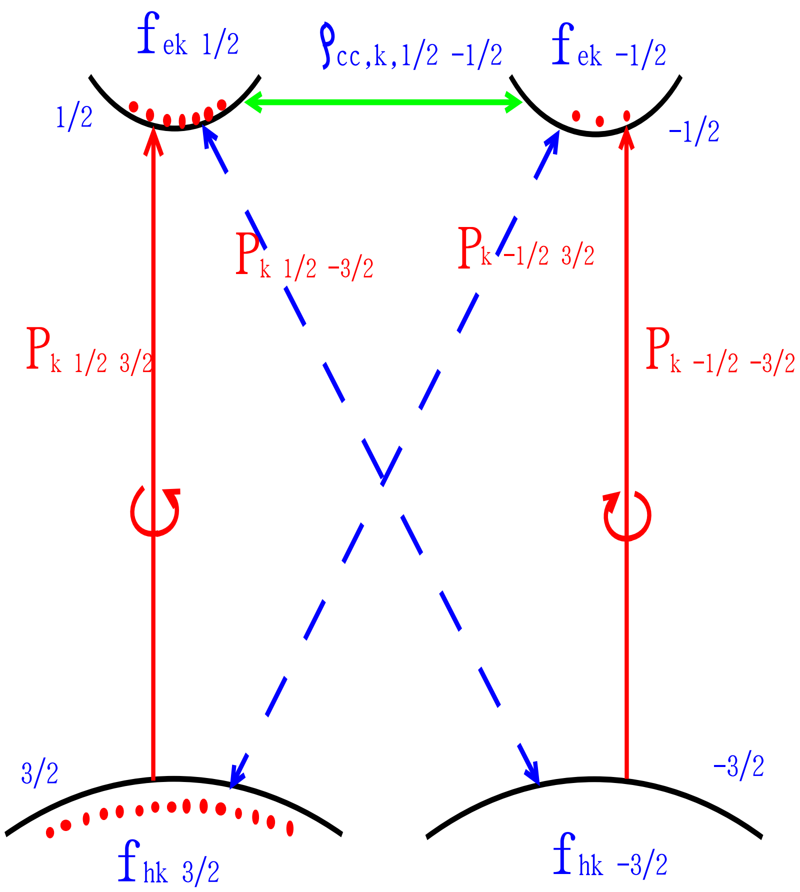
$\mathbf{\Omega}(\mathbf{k}) = (\gamma k_x(k_y^2 - \langle k_z^2\rangle), \gamma k_y(\langle k_z^2\rangle - k_x^2), 0)$/$(\alpha k_y, -\alpha k_x, 0)$.

Single particle theory: $\frac{1}{\tau} = \frac{\int_0^\infty dE_k(f_{k,1/2}-f_{k,-1/2})\tau_p(\mathbf{k})\overline{\mathbf{\Omega^2}(\mathbf{k})}}{\int_0^\infty dE_k(f_{k,1/2}-f_{k,-1/2})}$ $(\Omega\tau_p \ll 1)$

Key Points of Kinetic Spin Bloch Approach

- In the presence of the inhomogeneous broadening, any scattering (including the spin-conserving scattering), can cause irreversible spin dephasing.
- Coulomb scattering makes very important contribution to the spin dephasing and relaxation.
  [Wu, Eur. Phys. J. B **18**, 373 (00).]
  Ivchenko group [JETP Lett. **75**, 403 (02)]
  Harley group [PRL **89**, 236601 (02); PRB **75**, 165309 (07)]
- A real non-equilibrium microscopic approach to spin kinetics:
  - Scattering $\leftrightarrow$ Inhomogeneous Broadening
  - near and far away from the equilibrium
  - strong and weak scattering ($\Omega\tau_p \ll 1$ / $\Omega\tau_p > 1$)

Bloch Vector and Inhomogeneous Broadening



- Bloch Vector $\mathbf{U}(\mathbf{k},t)$:

$$U_1(\mathbf{k},t) = [P(\mathbf{k},t)e^{i\omega t} + c.c.]$$

$$U_2(\mathbf{k},t) = [P(\mathbf{k},t)e^{i\omega t} - c.c.]$$

$$U_3(\mathbf{k},t) = [f_c(\mathbf{k},t) - f_v(\mathbf{k},t)]$$

- Inhomogeneous Broadening:

$$\frac{d}{dt}\mathbf{U}(\mathbf{k},t) = \mathbf{\Omega}(\mathbf{k}) \times \mathbf{U}(\mathbf{k},t)$$

$$\mathbf{\Omega}(\mathbf{k}) = (\varepsilon_{c\mathbf{k}} - \varepsilon_{v\mathbf{k}} - \omega)\mathbf{e}_3 - \omega_R\mathbf{e}_1.$$

Faraday Rotation Angle & Spin Dephasing

- FR Angle [Sham *et al.*, PRL **74**, 4698 (1995)]:

$$\Theta_F(\tau) = C \sum_k \int \mathrm{Re}\Big[\bar{P}_{k\frac{1}{2}\frac{3}{2}}(t)E^{0*}_{\text{prob},-}(t-\tau) - \bar{P}_{k-\frac{1}{2}-\frac{3}{2}}(t)E^{0*}_{\text{prob},+}(t-\tau)\Big]dt$$

- The irreversible spin dephasing can be described by the incoherently-summed spin coherence, T_2

$$\rho(t) = \sum_k |\rho_{k,\uparrow\downarrow}(t)| \ .$$

- The optical dephasing is described by the incoherently-summed polarization [Kuhn & Rossi, PRL **69**, 977 (1992)],

$$P(t) = \sum_k |P_k(t)| \ .$$

- The spin relaxation time is determined from the spin polarization, T_1

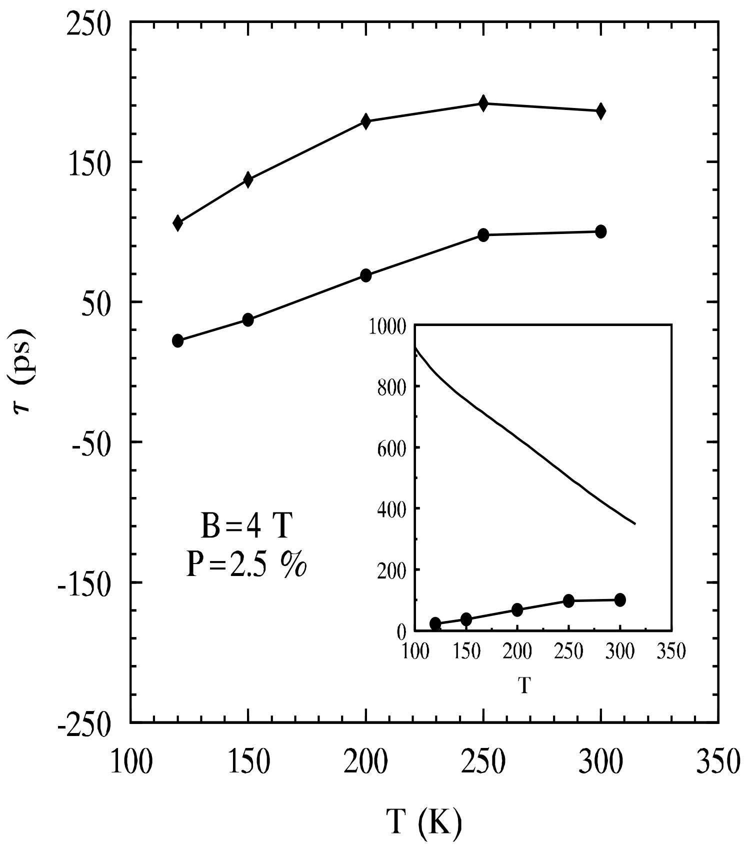
$$\Delta N = \sum_k (N_{k\uparrow} - N_{k\downarrow}) \ .$$

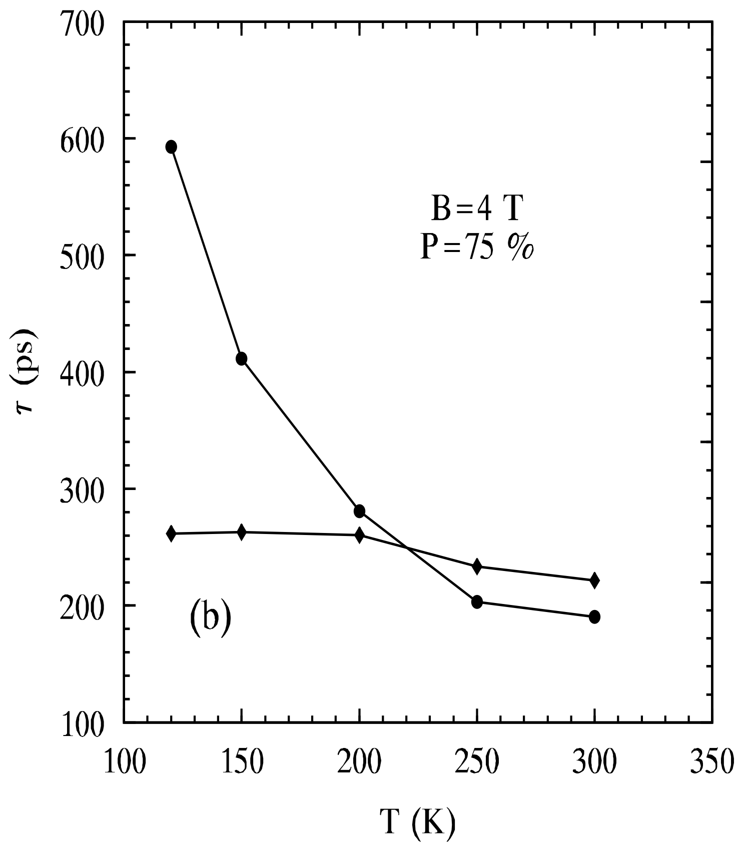
- The ensemble spin dephasing time is determined from the coherently-summed spin coherence, T_2^*

$$\rho'(t) = |\sum_k \rho_{k\uparrow\downarrow}| \ .$$

Temperature Dependence of Spin Dephasing

[Weng and Wu, PRB **68**, 075312 (2003)]

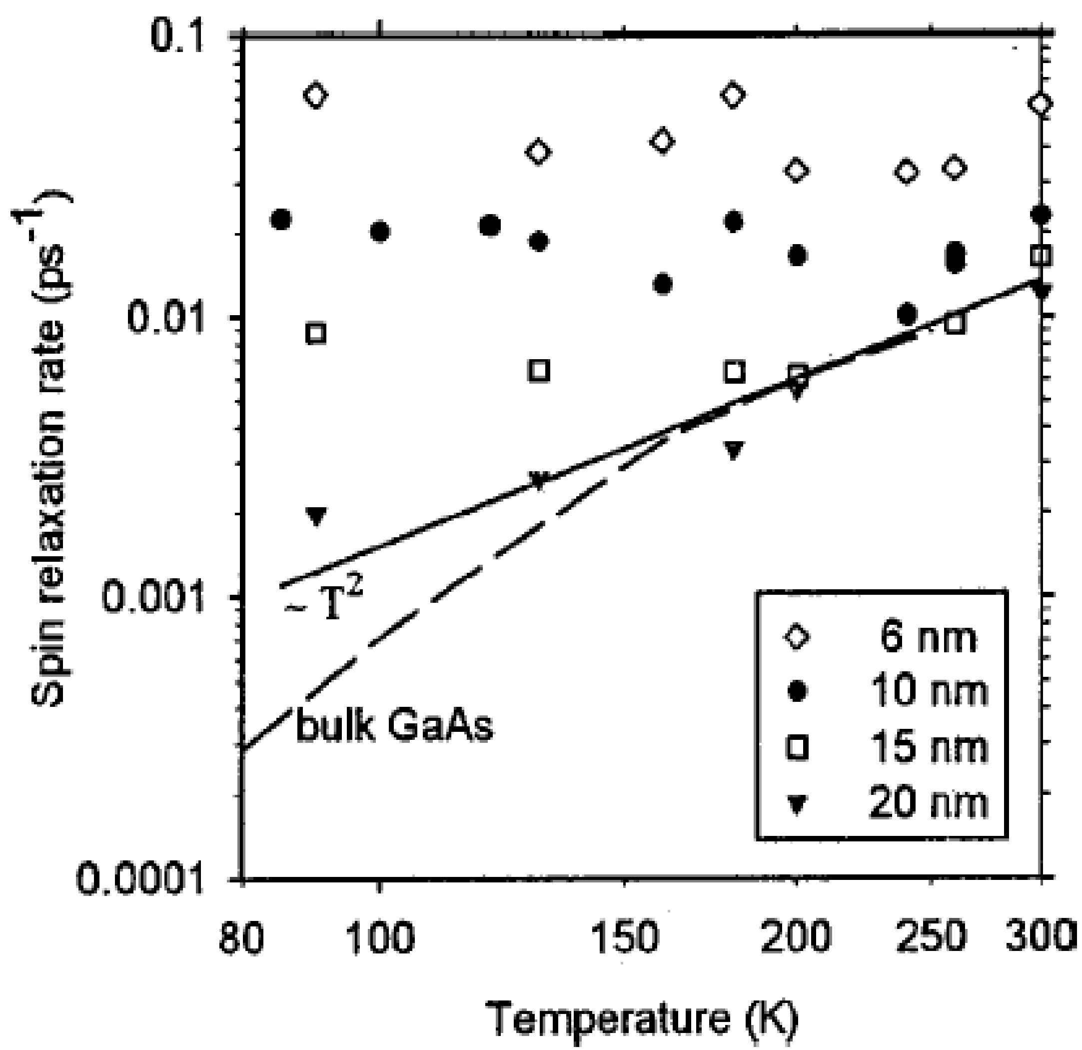




$a = 15$ nm, $n = 4 \times 10^{11}$ cm^{-2}

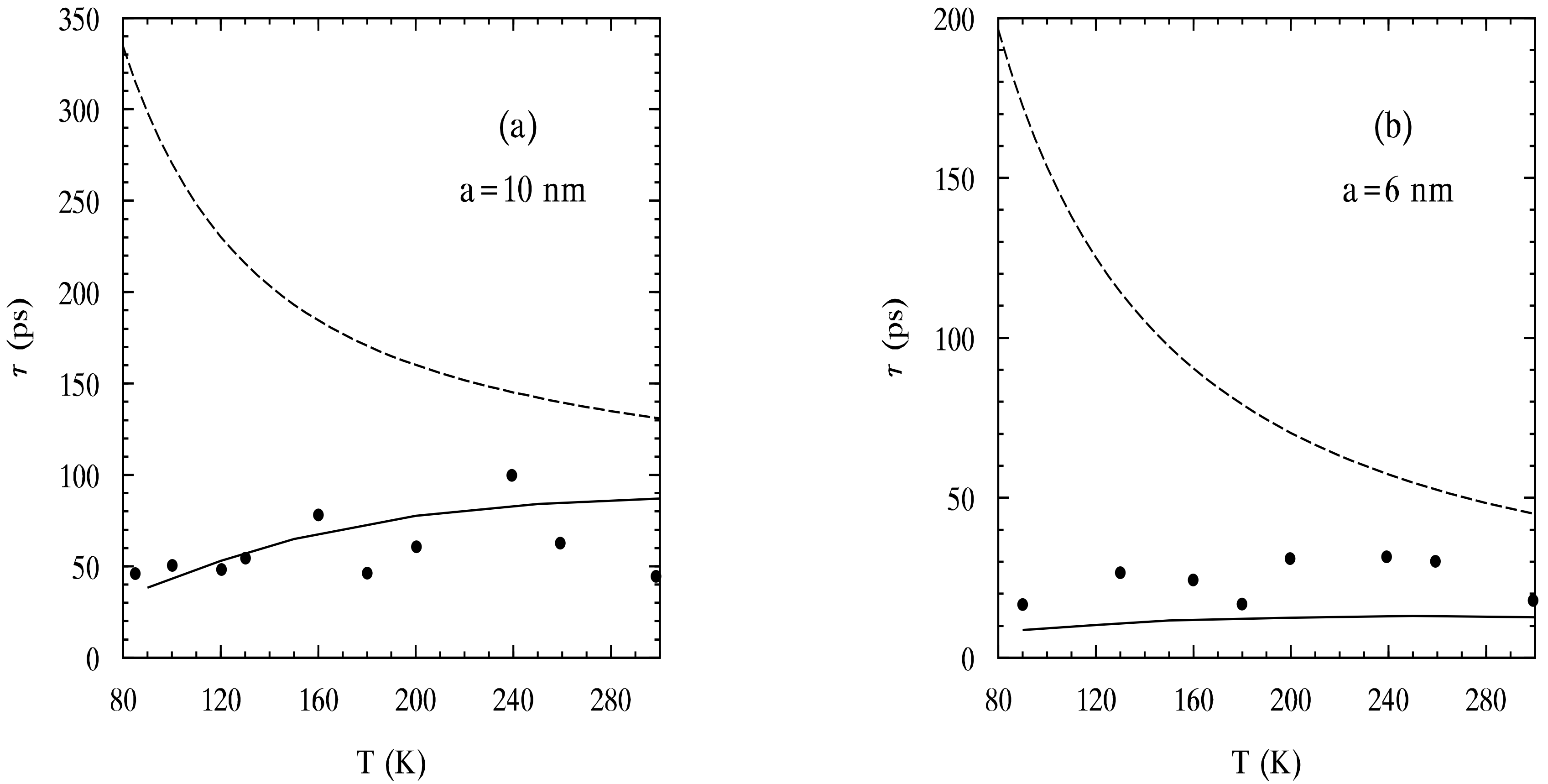
Experiment

A. Malinowski *et al.*, PRB **62**, 13034 (2000)



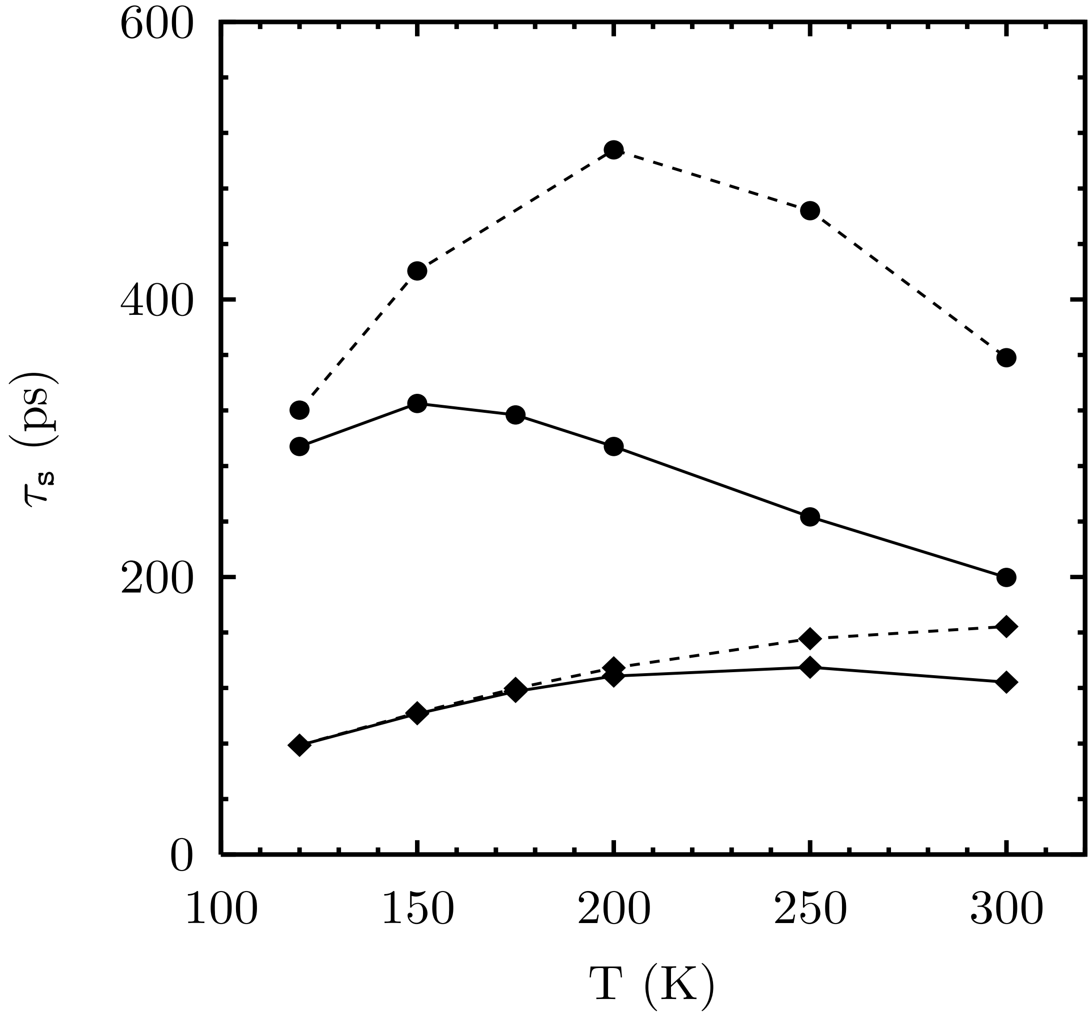
Comparison with Experiment

[Weng and Wu, Chin. Phys. Lett. **22**, 671 (2005)]



Different Well Width

[Weng and Wu, PRB **70**, 195318 (2004)]



$a = 17.8$ nm(●)/12.7 nm (♦)

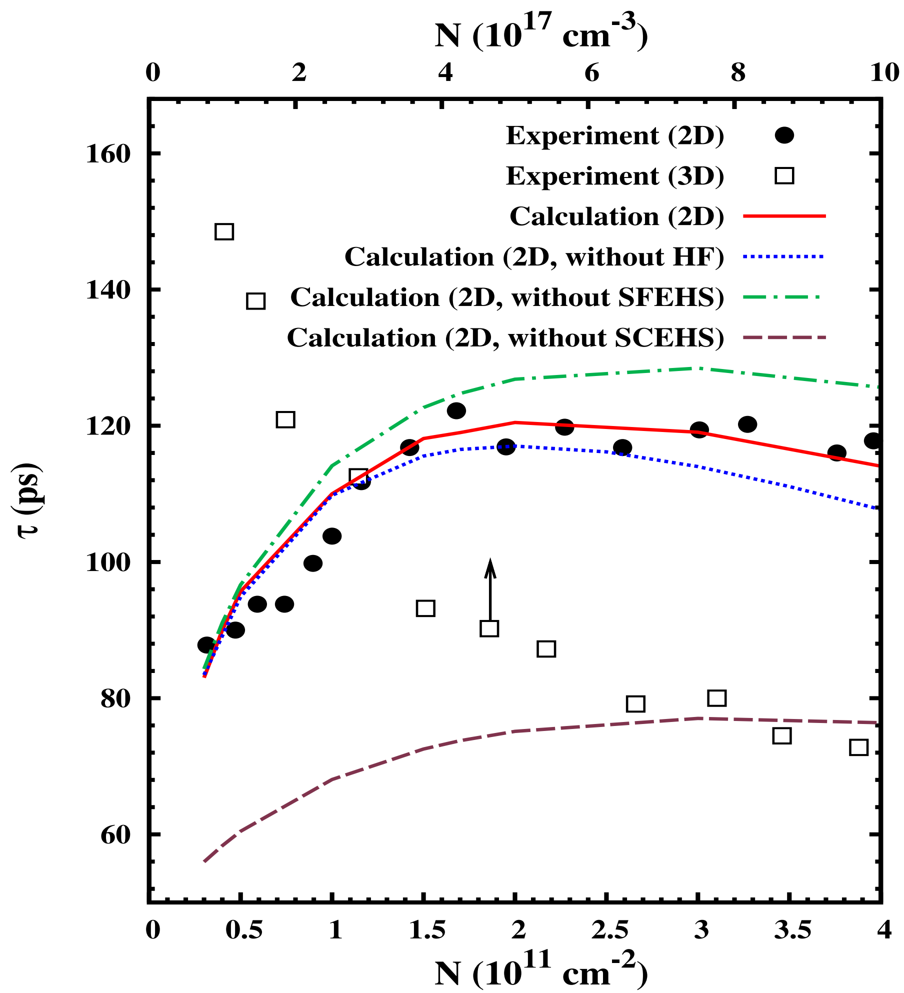
$$h_{nn',x}(\mathbf{k}) = \gamma k_x (k_y^2 - \langle n|k_z^2|n\rangle)\delta_{nn'}$$
$$h_{nn',y}(\mathbf{k}) = \gamma k_y (\langle n|k_z^2|n\rangle - k_x^2)\delta_{nn'}$$
$$h_{nn',z}(\mathbf{k}) = \gamma \langle n|k_z|n'\rangle (k_x^2 - k_y^2).$$

$$\langle n|k_z^2|n\rangle = (\frac{n\pi}{a})^2$$

- Jiang and Wu, PRB **72**, 033311 (2005).
- Holleitner *et al.*, New J. Phys. **9**, 342 (2007).

Density Dependence of an Intrinsic GaAs QW

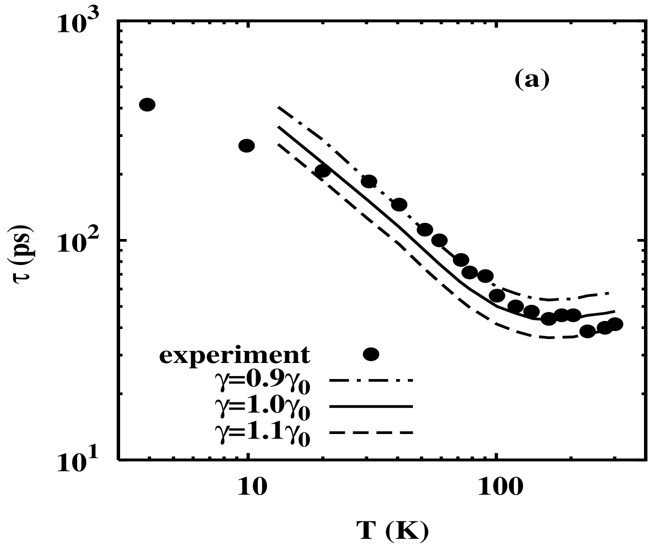
[Teng, Zhang, Lai, and Wu, Europhys. Lett. **84**, 27006 (2008)]

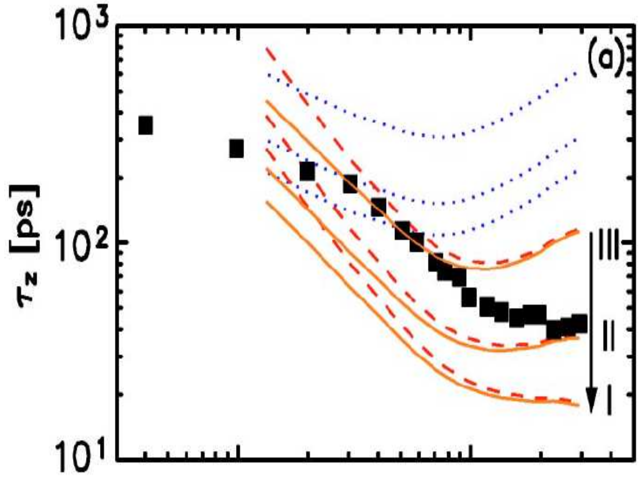


Lü, Cheng, and Wu, PRB **73**, 125314 (2006).

Comparison with another Experiment

[Zhou, Cheng, and Wu, PRB **75**, 045305 (2007)]

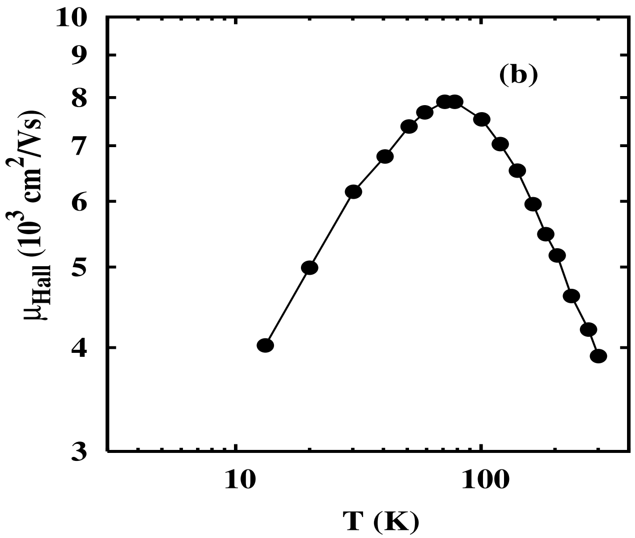




Experiments: Ohno *et al.*, Physica E **6**, 817 (2000).

Theory: Kainz *et al.*, PRB **70**, 195322 (2004).

$a = 7.5$ nm; $n = 4\times 10^{10}$ cm^{-2}

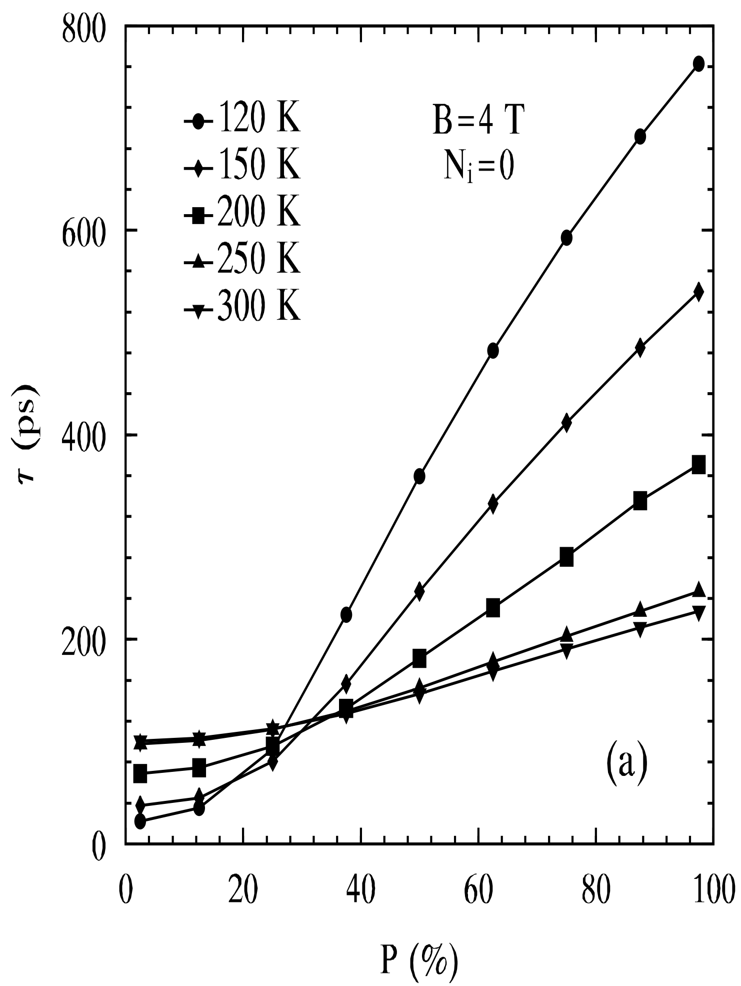


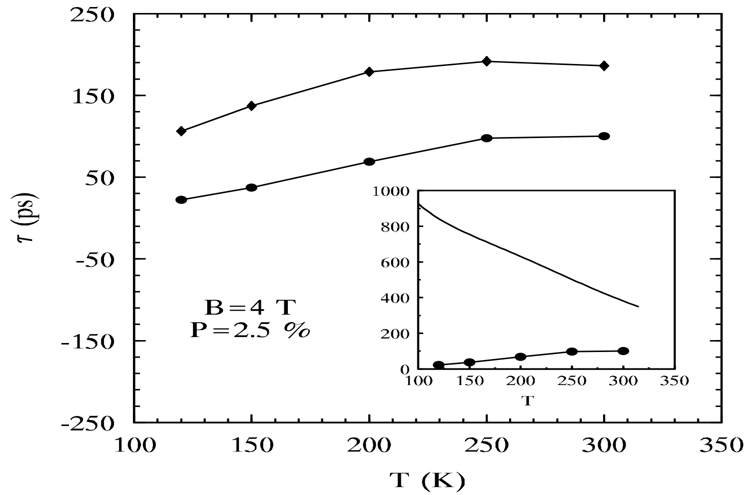
$$\gamma = (4/3)(m^*/m_{cv})(1/\sqrt{2m^{*3}E_g})(\eta/\sqrt{1-\eta/3})$$

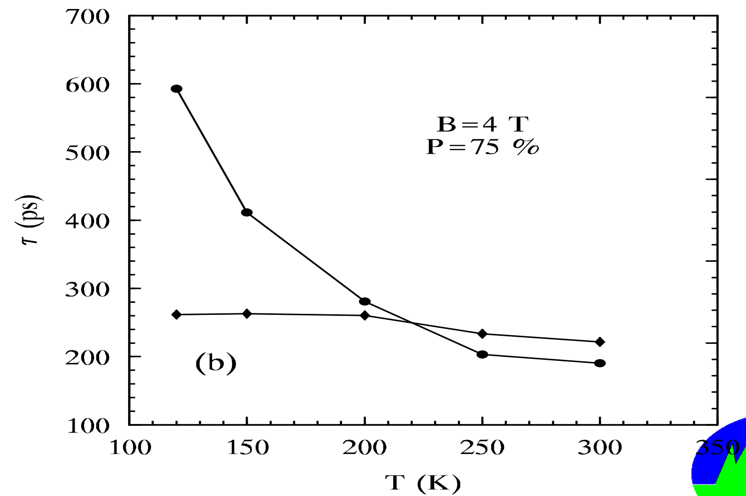
$$\gamma_0 \longrightarrow m_{cv} = m_0$$

Spin Dephasing at High Spin Polarization

[Weng and Wu, PRB **68**, 075312 (2003)]





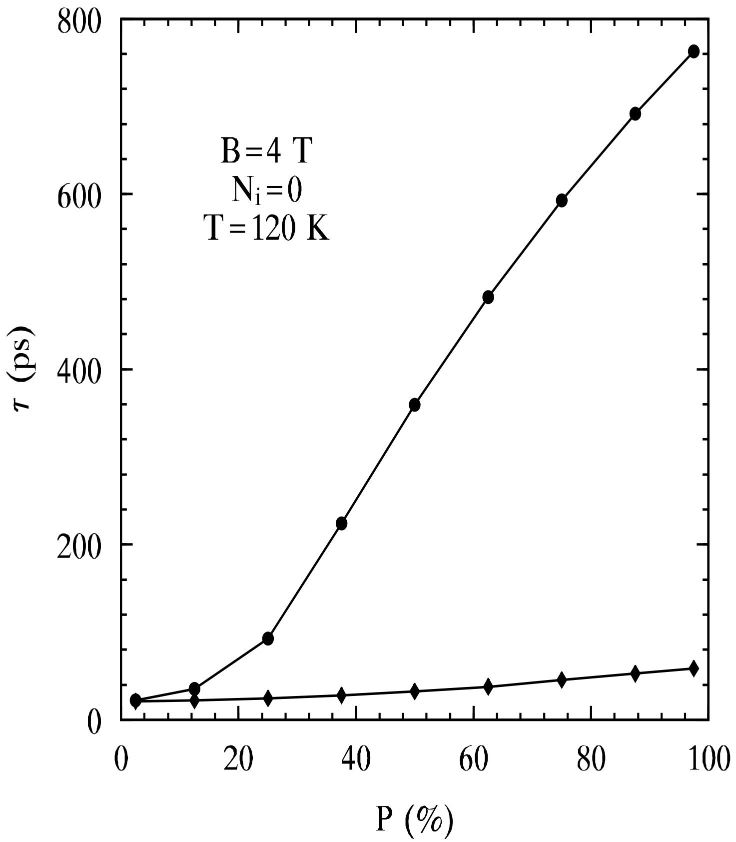


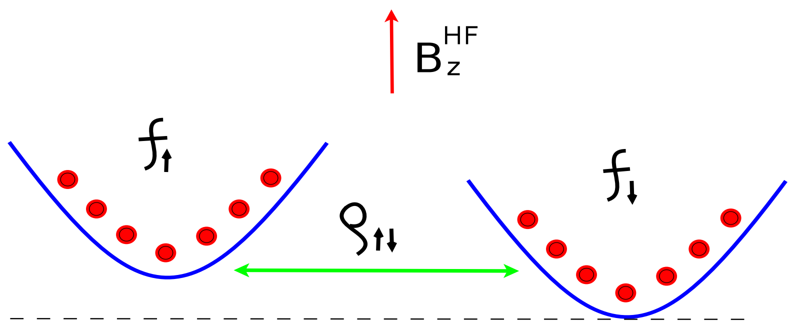
“Detuning” Effect from HF Term

[Weng and Wu, PRB **68**, 075312 (2003)]

Longitudinal effective magnetic field from the HF term:

$$B_z^{\mathrm{HF}}(\mathbf{k}) = \frac{2}{g\mu_B}\sum_{\mathbf{q}} V_{\mathbf{q}}(f_{\mathbf{k}+\mathbf{q}\frac{1}{2}} - f_{\mathbf{k}+\mathbf{q}-\frac{1}{2}})$$

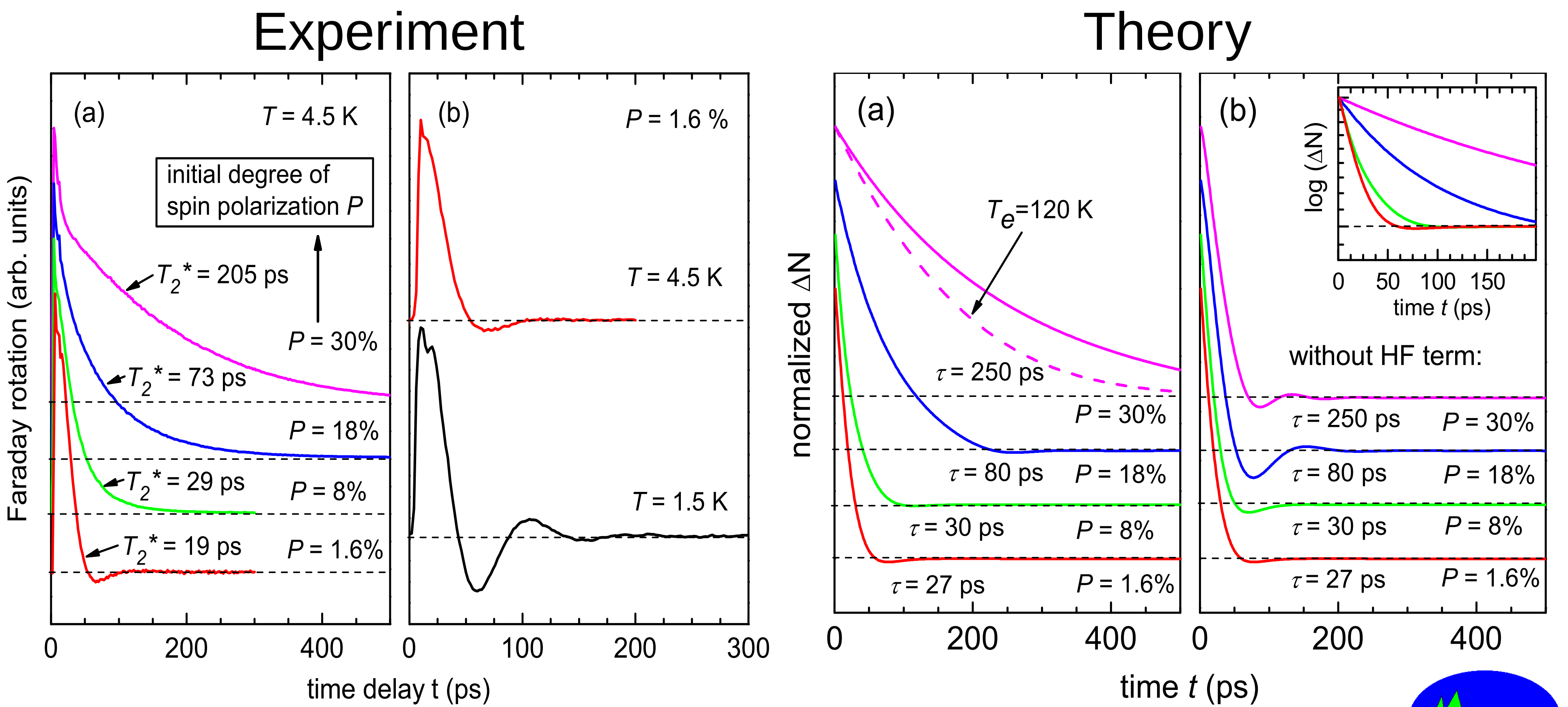




Zhang *et al.*, EPL **83**, 47006 (08).

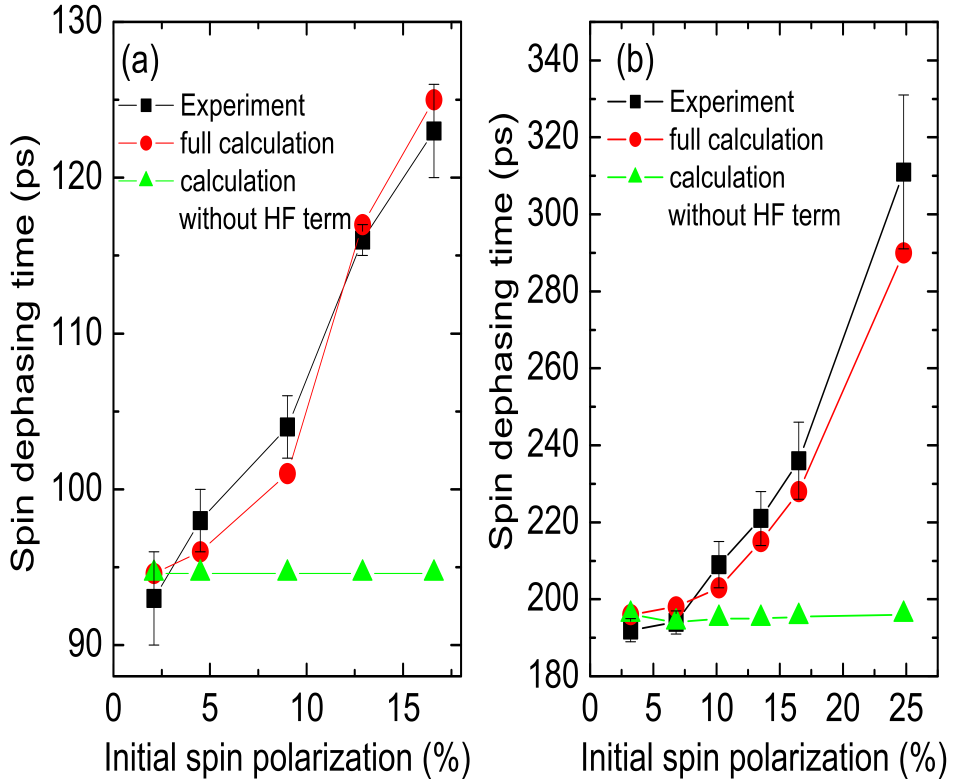
Experimental Realization

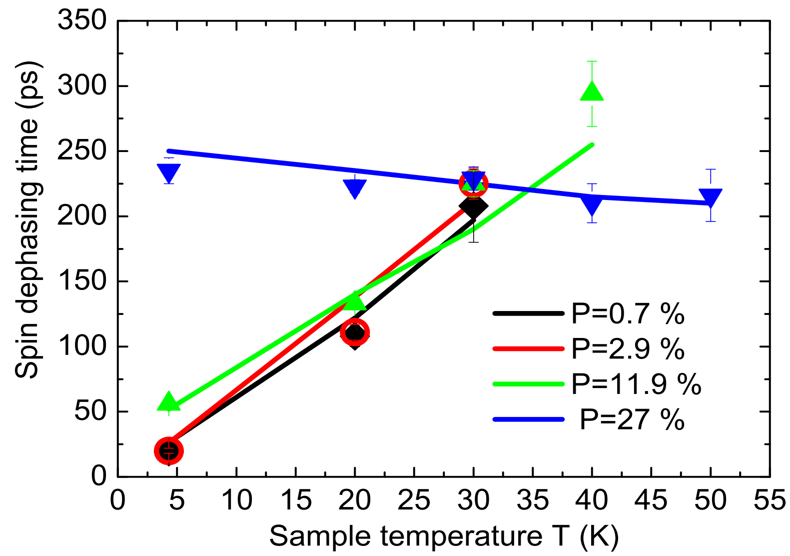
[Stich, Zhou, Korn, Schulz, Schuh, Wegscheider, Wu, and Schüller, PRL **98**, 176401 (2007)]

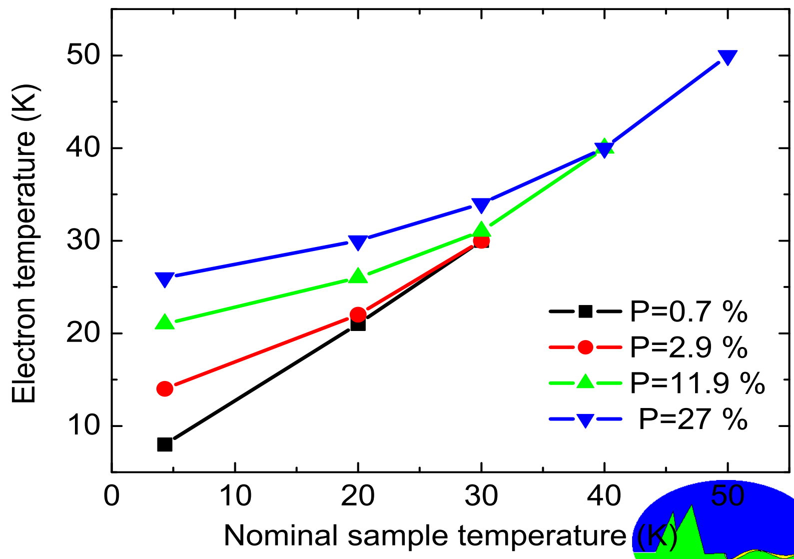


Fixed Excitation and T Dependence

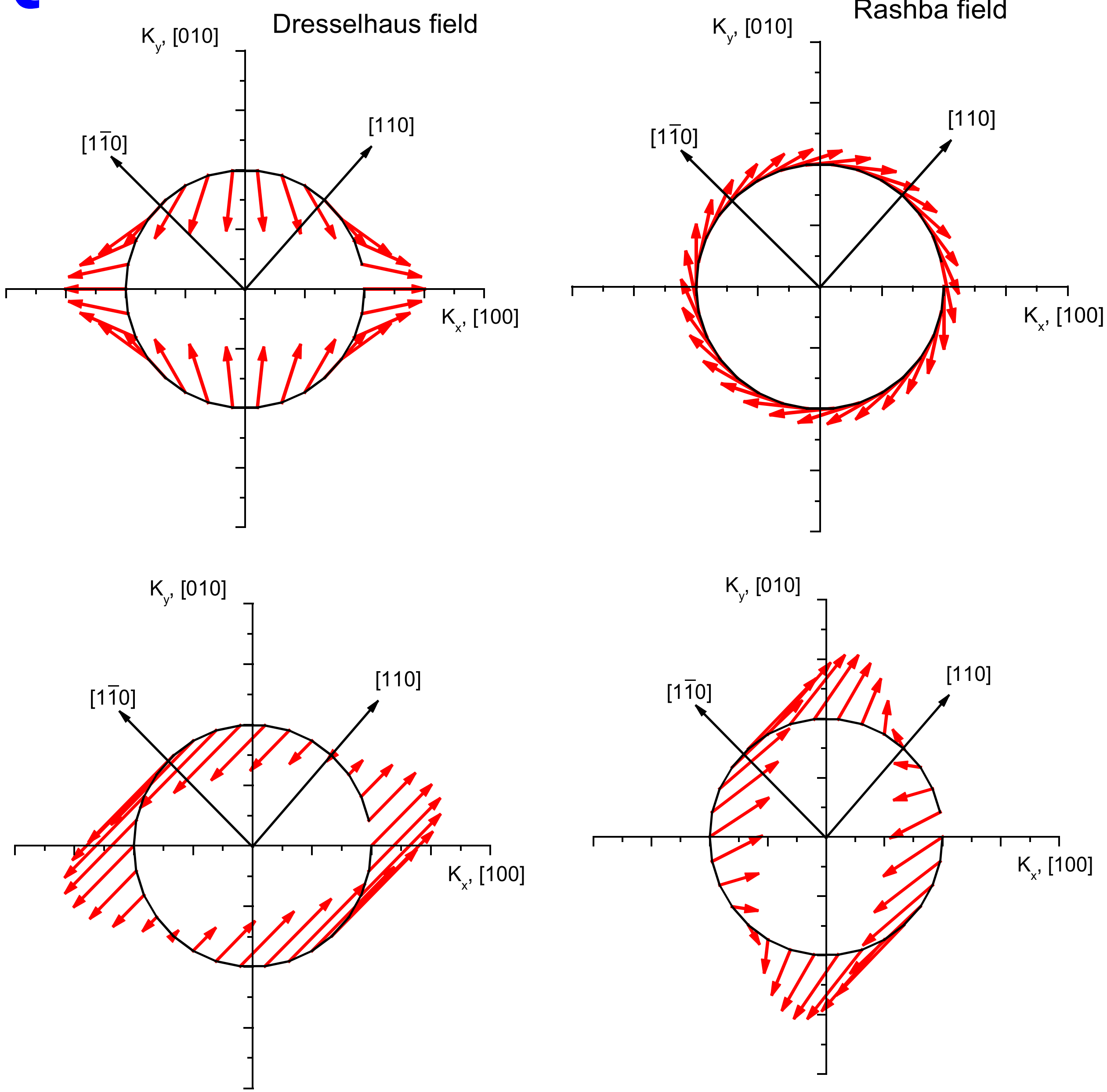
[Stich, Zhou, Korn, Schulz, Schuh, Wegscheider, Wu, and Schüller, PRB **76**, 205301 (2007)]





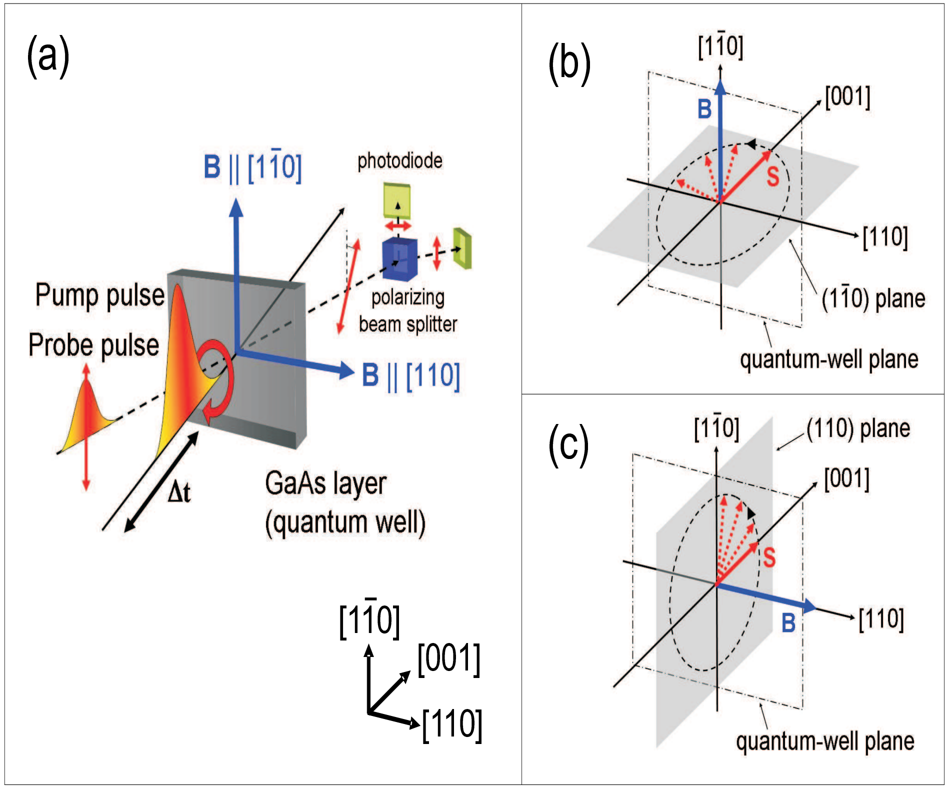


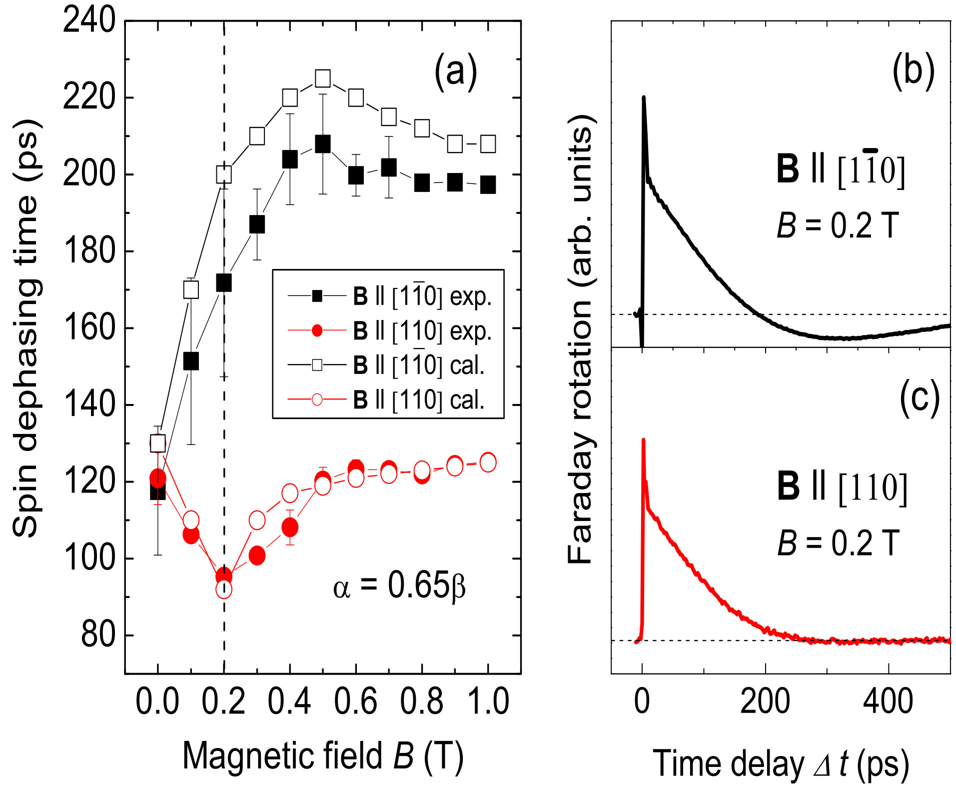
Inhomogeneous Broadening $\Omega(\mathbf{k})$ of (001) QW with Dresselhaus/Rashba Coupling



Magneto-Anisotropy of Spin Dephasing in High-Mobility GaAs [001] QW

[Stich, Jiang, Korn, Schulz, Schuh, Wegscheider, Wu, and Schüller, PRB **76**, 073309 (2007)]

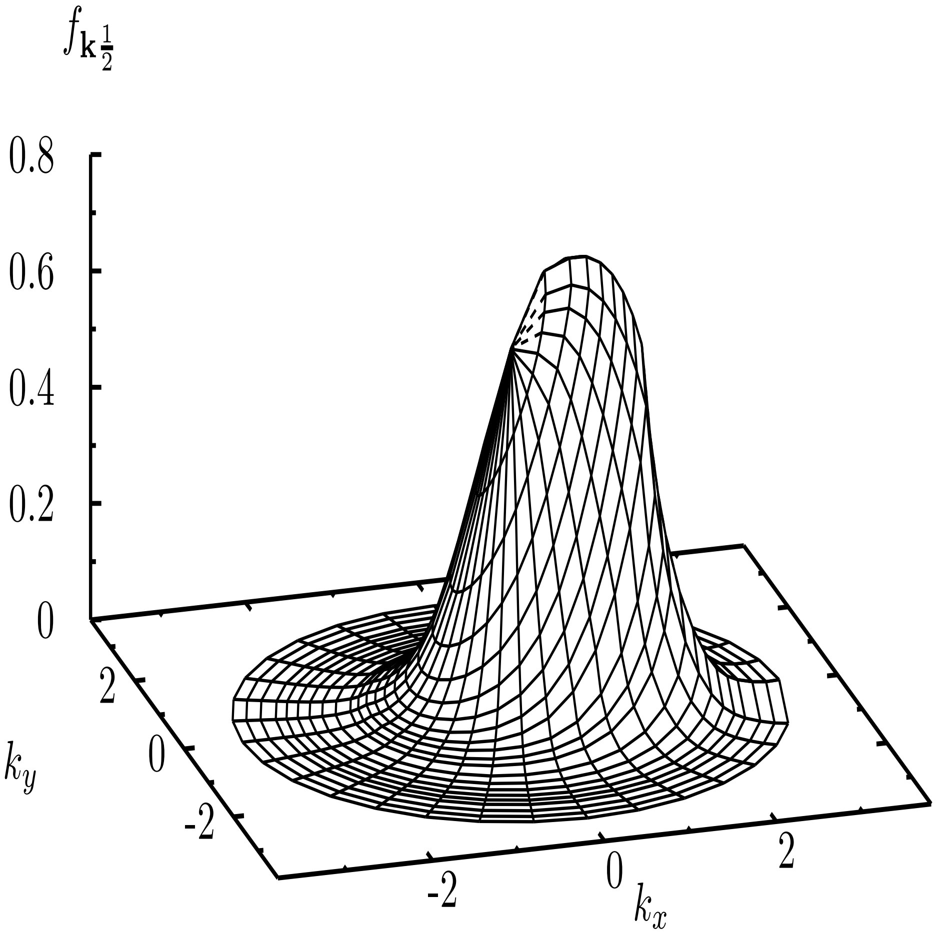


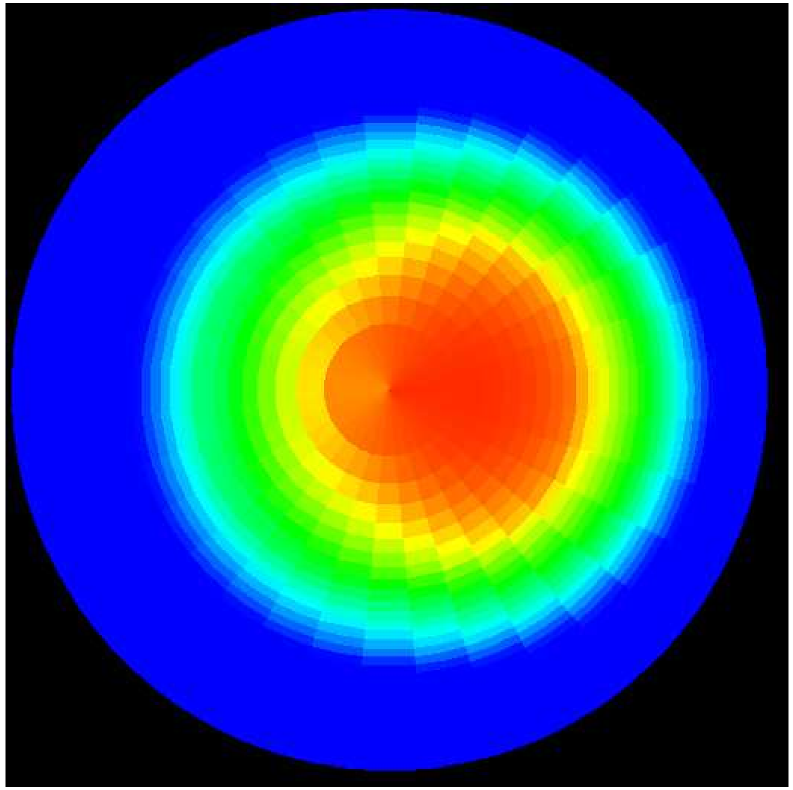


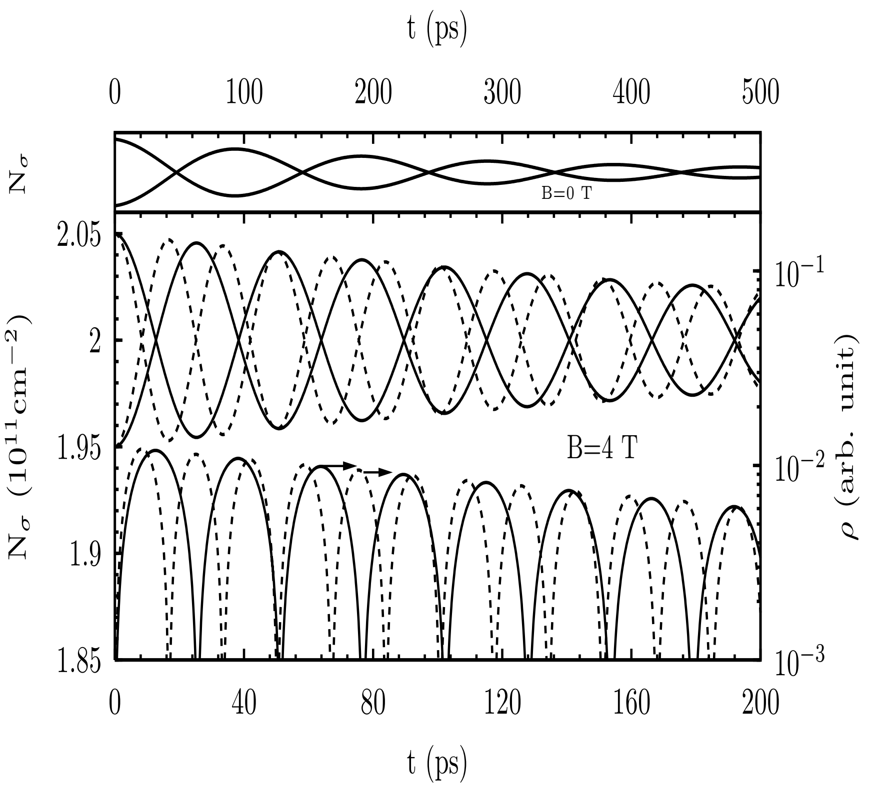
[1$\bar{1}$0]: $(\alpha-\beta)k_x$; [110] (x-axis): $(\alpha+\beta)k_y$.

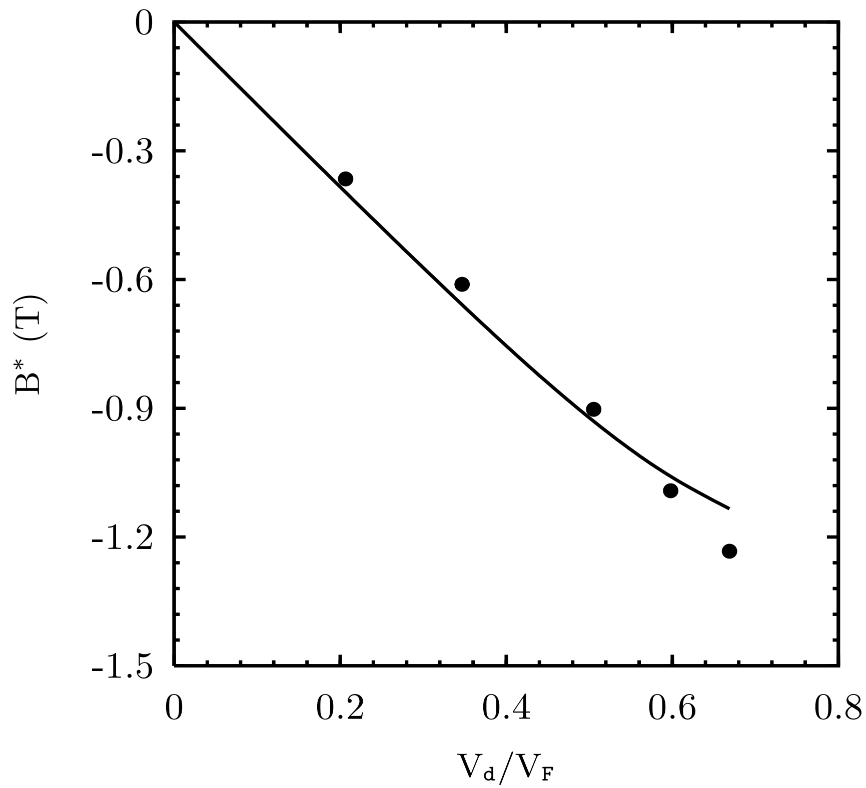
Hot-Electron Effect in Spin Kinetics

[Weng, Wu and Jiang, PRB **69**, 245320 (2004)]









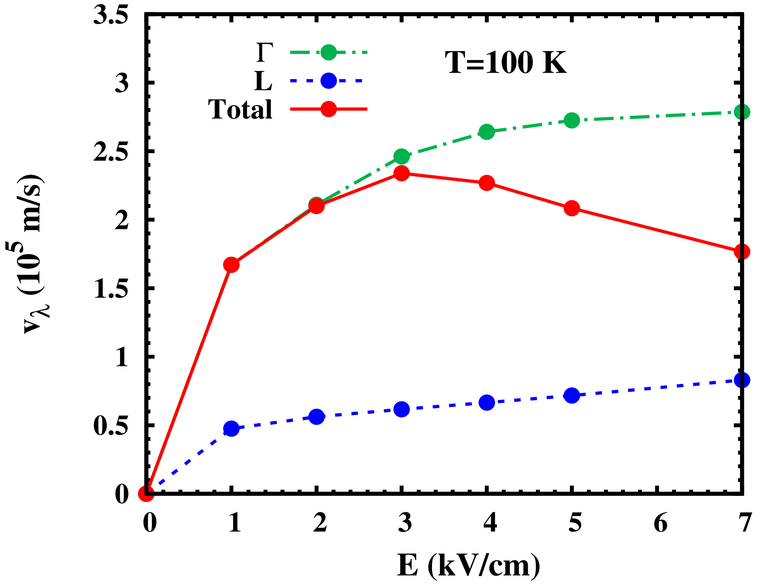
$$h_x = \gamma k_x(k_y^2 - \langle k_z^2 \rangle) \text{ and } h_y = \gamma k_y(\langle k_z^2 \rangle - k_x^2)$$

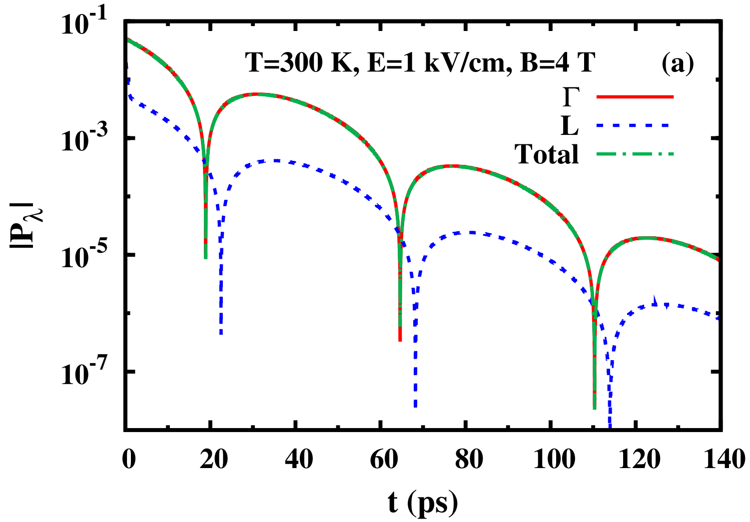
$$\mathbf{B}_{\mathtt{tot}} = \mathbf{B} + \mathbf{B}^* = \mathbf{B} + \frac{1}{g\mu_B}\frac{\int d\mathbf{k}(f_{\mathbf{k}1/2} - f_{\mathbf{k}-1/2})\mathbf{h}(\mathbf{k})}{\int d\mathbf{k}(f_{\mathbf{k}1/2} - f_{\mathbf{k}-1/2})}$$

$$B^* = \gamma m^{*3}\mu E\{E_f/[2(1 - e^{-E_f/T_e})] - E_c\}/g\mu_B.$$

Multivalley Spin Dynamics in the presence of High Electric Fields

[Zhang, Zhou, and Wu, PRB **77**, 235323 (2008)]



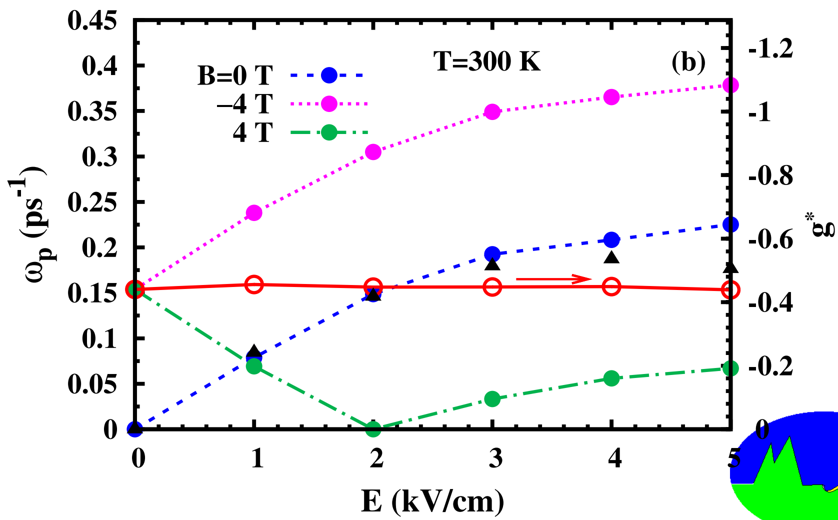


$$g_\Gamma = -0.04, \qquad g_L = 1.77$$

[Shen, Weng, Wu, JAP **104**, 063719 (2008)]

$$\mathbf{h}_L(\mathbf{k}_L) = \beta(k_L^x, k_L^y, 0) \times \hat{\mathbf{n}}$$

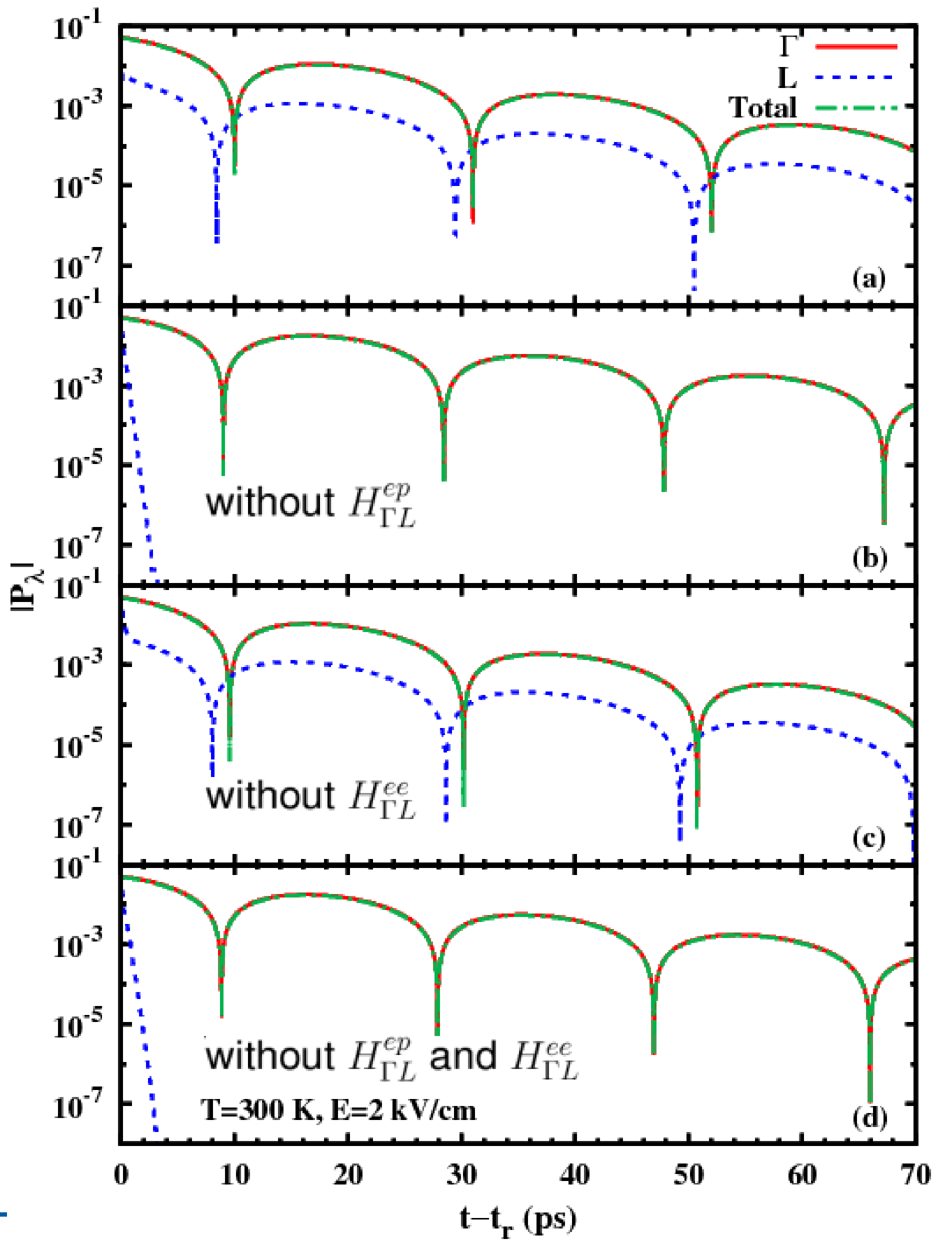
[Fu, Weng, and Wu, Physica E **40**, 2890 (2008)]



http://wu.ustc.edu.cn/~mwu/

Inter-valley Electron-Phonon Scattering

[Zhang, Zhou, and Wu, PRB **77**, 235323 (2008)]

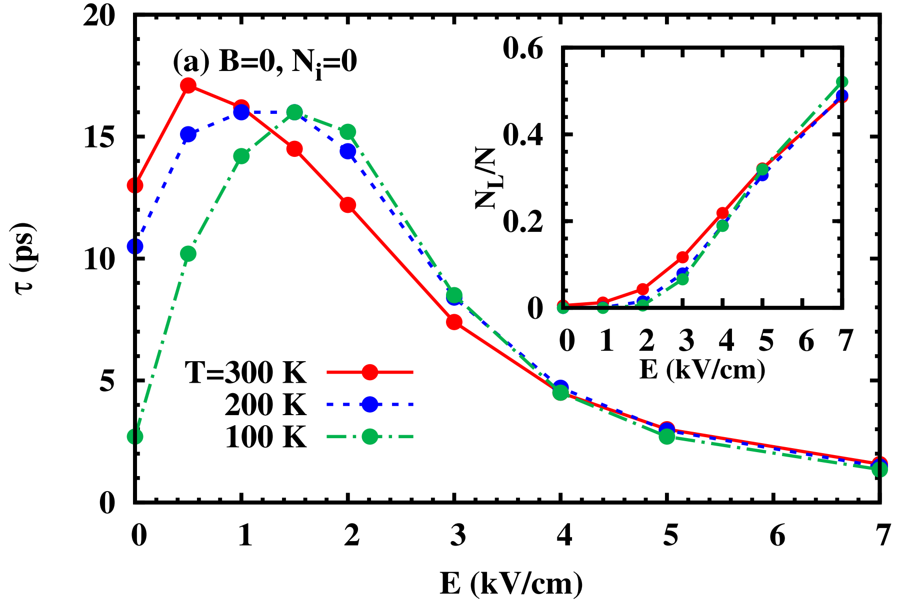


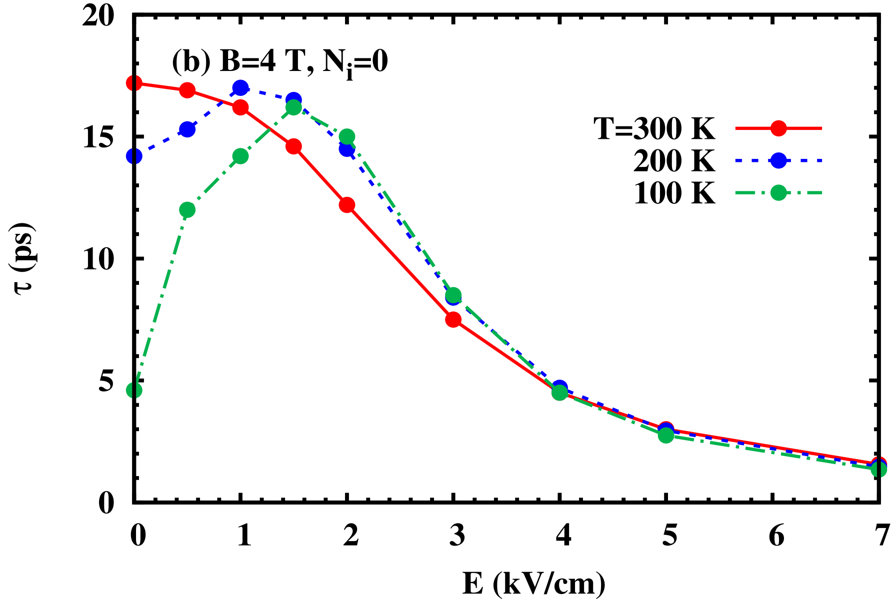
Similar to multi-subband case:

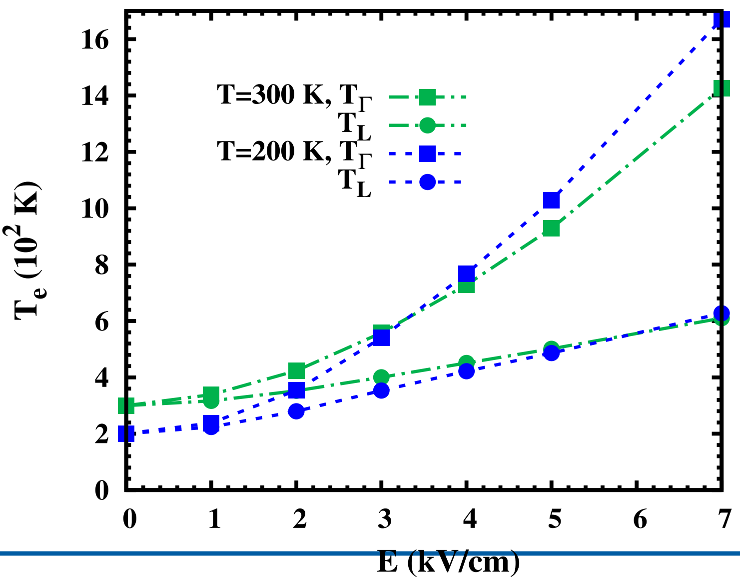
- Prediction: Identical spin relaxation times for different subbands due to *inter-subband Coulomb scattering [Weng and Wu, PRB* **70**, *1953318 (2004)]*
- *Experimental verification: [Fang* et al., *Europhys. Lett.* **83**, *47007 (2008)]*

Spin manipulation with in-plane Electric Field

[Zhang, Zhou, and Wu, PRB 77, 235323 (2008)]



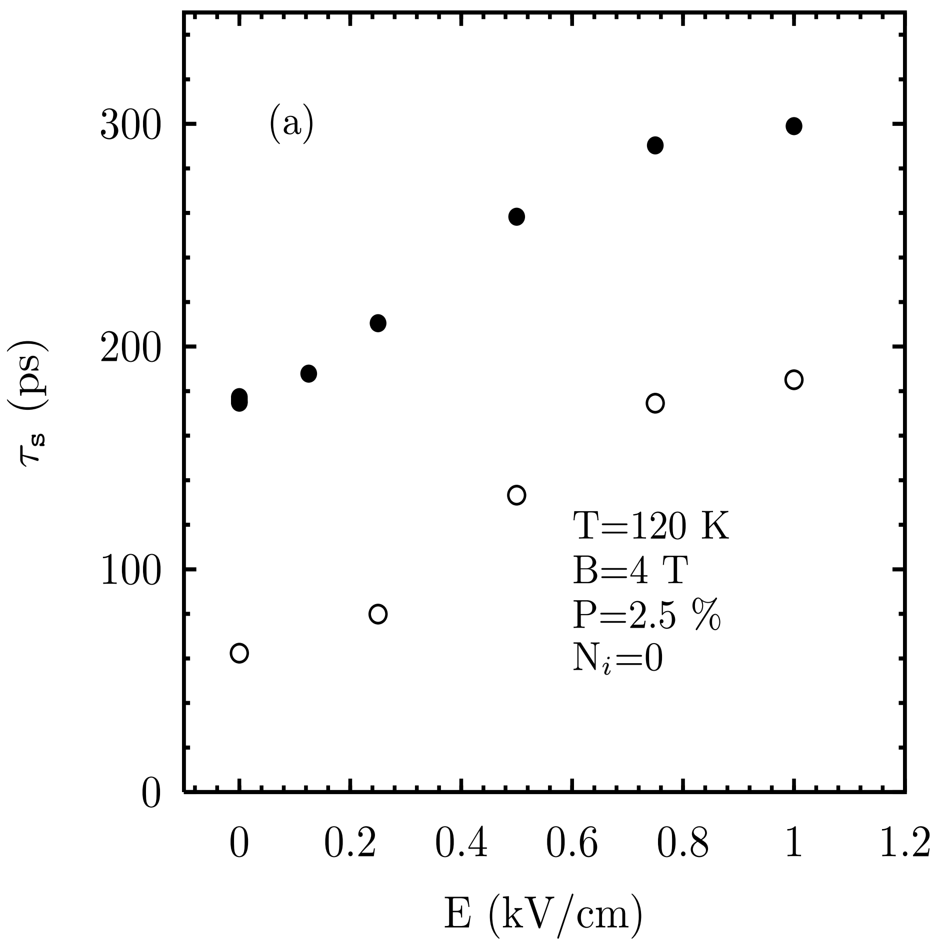


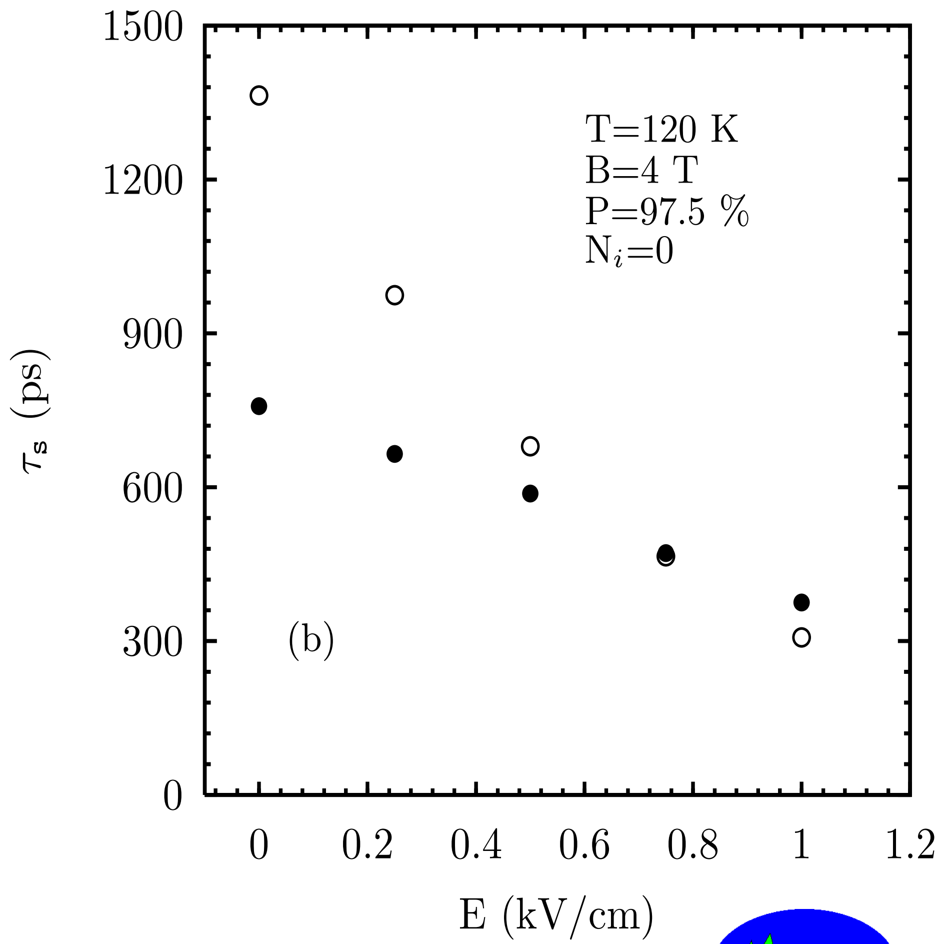


http://wu.ustc.edu.cn/~mwu/

Coulomb Scattering in Spin Dephasing

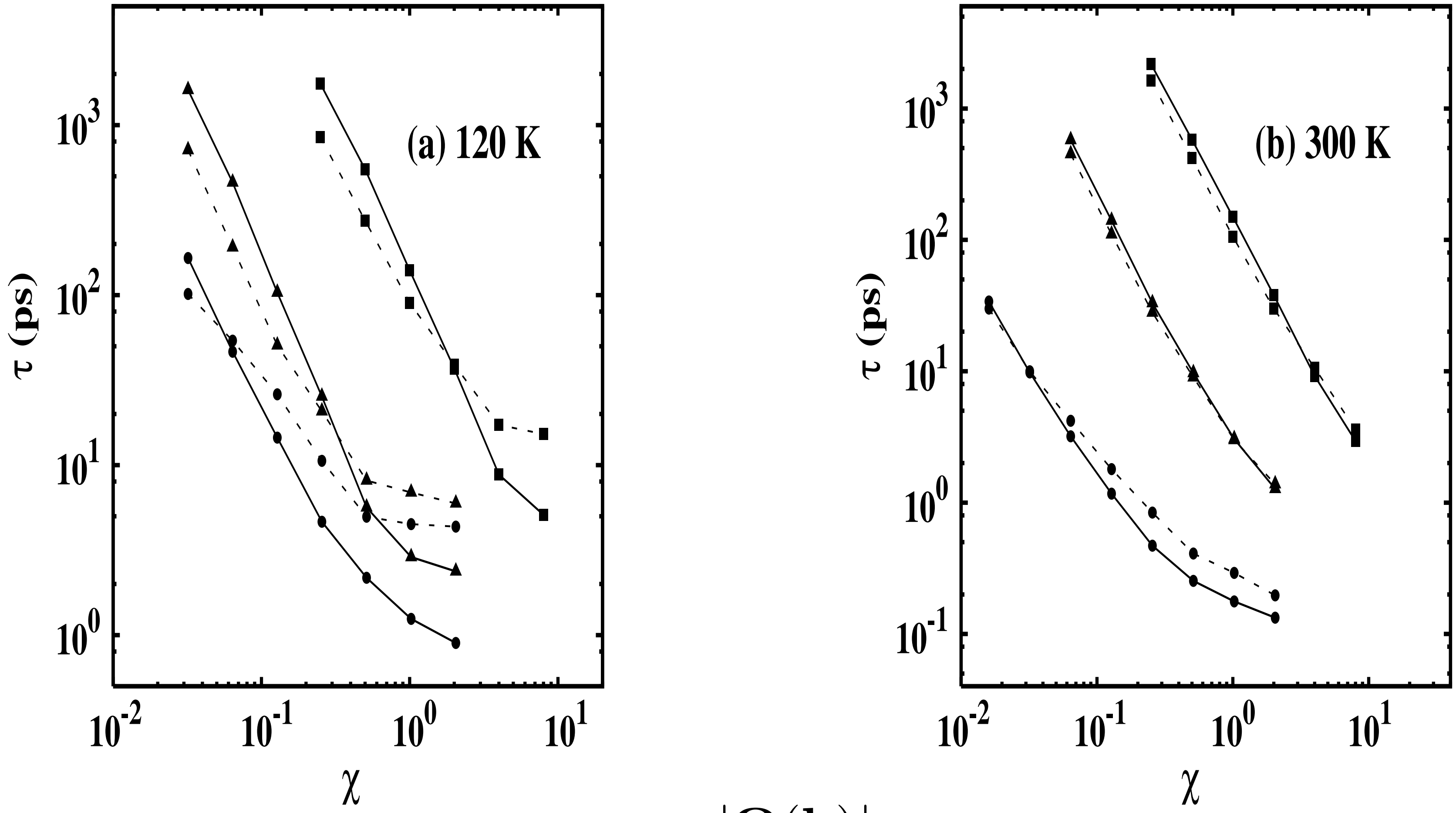
[Weng, Wu and Jiang, PRB **69**, 245320 (2004)]





Increase or Decrease

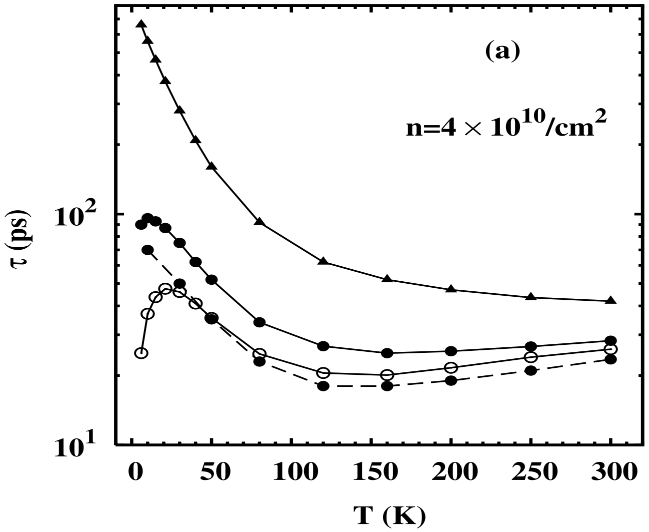
[Lü, Cheng, and Wu, PRB **73**, 125314 (2006)]

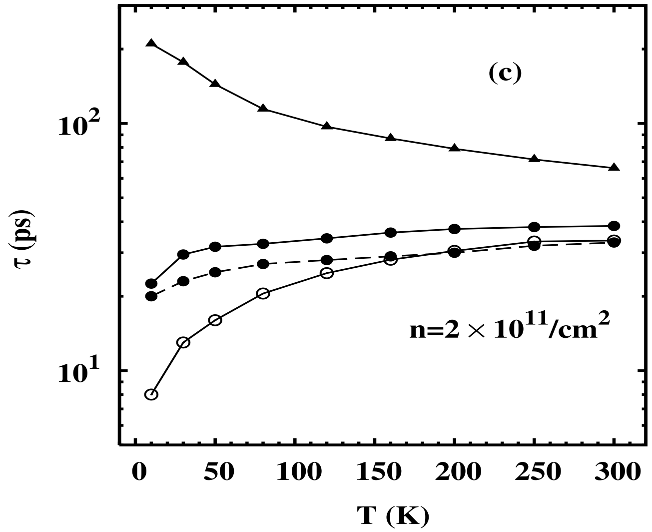


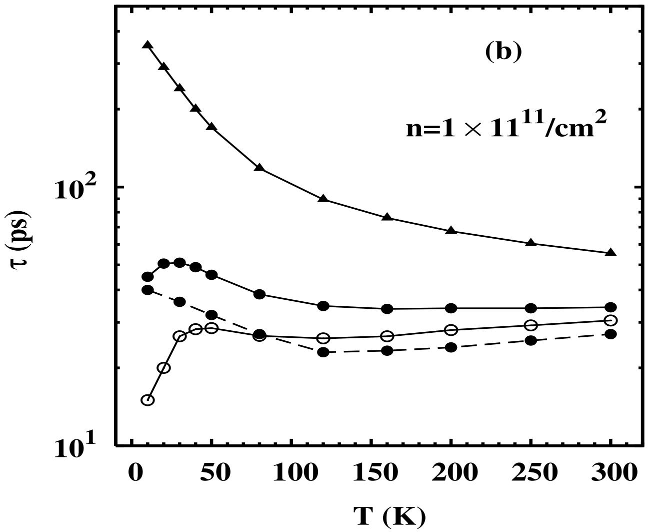
$$\chi|\mathbf{\Omega}(\mathbf{k})|\tau_p$$

Coulomb Scattering Induced Spin Relaxation

[Zhou, Cheng, and Wu, PRB **75**, 045305 (2007)]







$a = 7.5$ nm, $\gamma = \gamma_0$

Degenerate limit (Low T): $\tau_p^{ee} \propto T^{-2}$

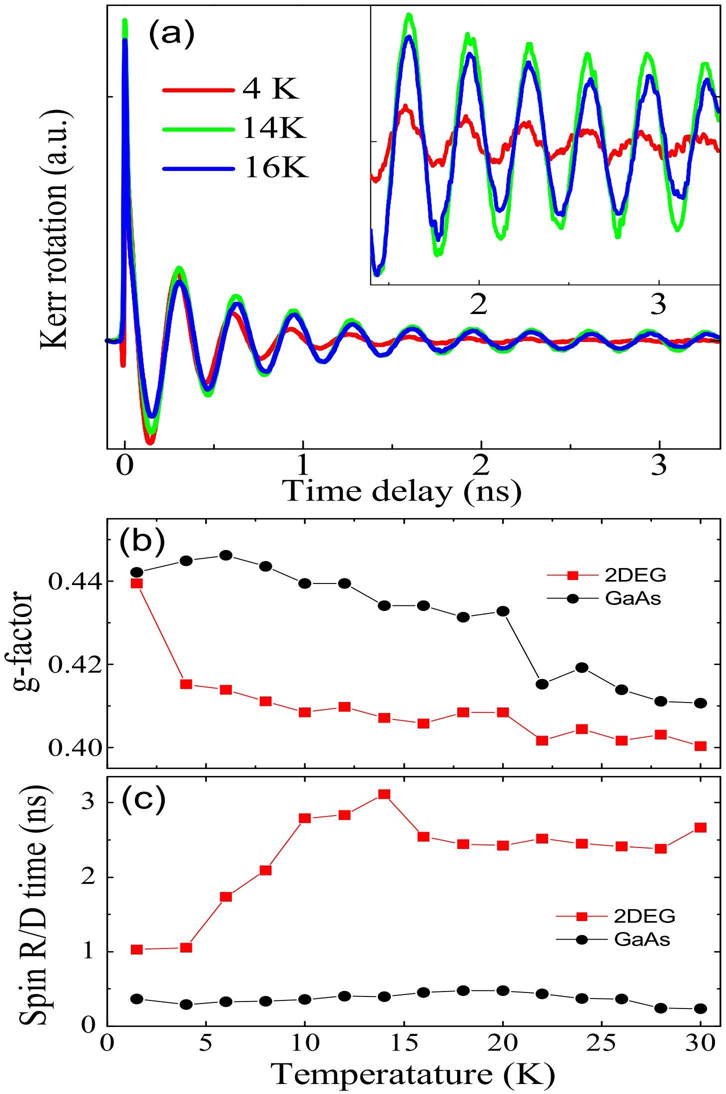
Non-degenerate limit (High T): $\tau_p^{ee} \propto T$

Bronold *et al.*, PRB **70**, 245210 (2004).

$T_c \sim E_F / k_B$

Experiment by Y. Ji

[Ruan *et al.*, PRB **77**, 193307 (2008)]



Markovian Approximation

Heavy hole-LO phonon scattering term in $\dot{\rho}_{\mathbf{k}}(t)|_{scat}$:

$$\dot{\rho}_{\mathbf{k}}(t)|_{scat}^{hp} = [A_{\mathbf{k}}(<,>)(t) - A_{\mathbf{k}}(>,<)(t)] + [...]^{\dagger}$$

$$A_{\mathbf{k}}(<,>)(t) = \frac{1}{\hbar^2}\int_{-\infty}^{t} d\tau \sum_{\mathbf{Q}} g_{\mathbf{Q}}^2 (N^{>} e^{i\omega_0(t-\tau)} + N^{<} e^{-i\omega_0(t-\tau)}) \times e^{-\frac{i}{\hbar}(E_{\mathbf{k-q}}-E_{\mathbf{k}})(t-\tau)} \rho_{\mathbf{k-q}}^{<}(\tau)\rho_{\mathbf{k}}^{>}(\tau)$$

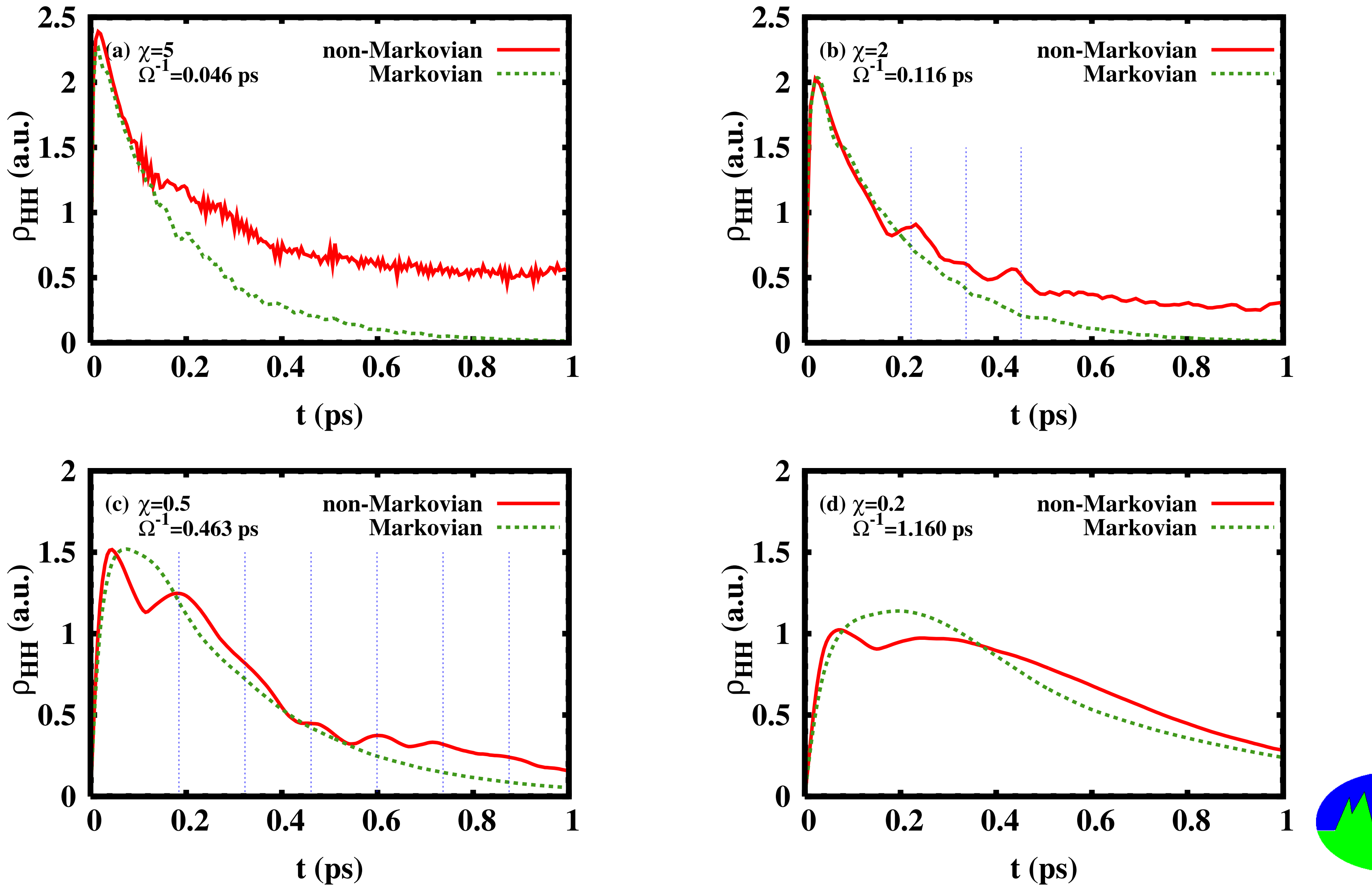
Markovian approximation:

$$\int_{-\infty}^{t} d\tau e^{i\omega(t-\tau)} u(\tau) \approx \pi\delta(\omega) u(t)$$

- $u(\tau) \rightarrow u(t) \Longrightarrow$ Time localization
- $\delta(\omega) \Longrightarrow$ Energy conservation

Non-Markovian Kinetics in p-type GaAs QW

[Zhang and Wu, PRB **76**, 193312 (2007)]

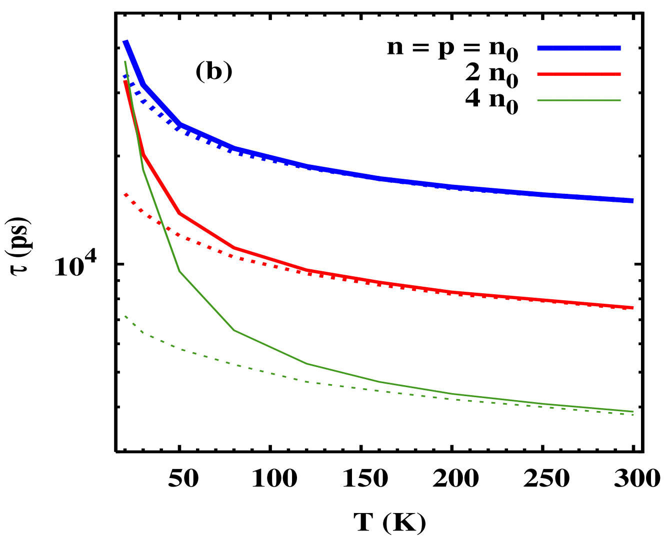


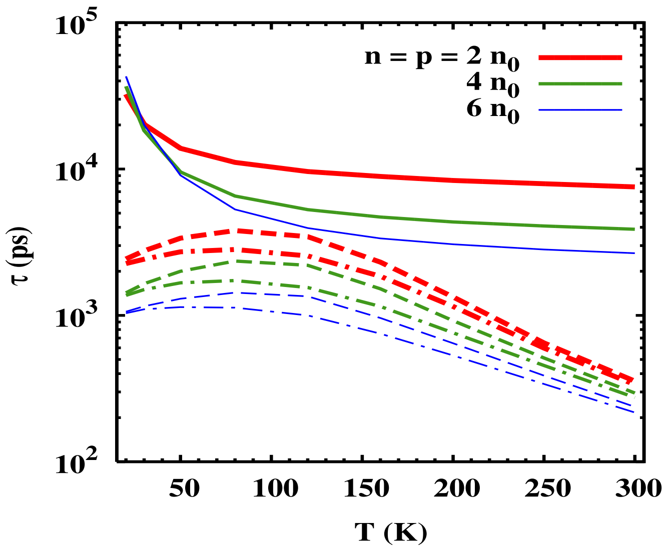
BAP Mechanism from KSBE Approach

[Zhou and Wu, PRB **77**, 075318 (2008)]

- $[2\tau^1_{\text{BAP}}(\mathbf{k})]^{-1} = 2\pi\sum_{\mathbf{k}',\mathbf{q}}\delta(\varepsilon^e_{\mathbf{k}-\mathbf{q}} - \varepsilon^e_{\mathbf{k}} + \varepsilon^h_{\mathbf{k}'} - \varepsilon^h_{\mathbf{k}'-\mathbf{q}})|M(\mathbf{K}-\mathbf{q})|^2[(1-f^h_{\mathbf{k}'})f^h_{\mathbf{k}'-\mathbf{q}}].$
- KSBE Approach:

$$\left.\frac{\partial f_{\mathbf{k},\sigma}}{\partial t}\right|_{\text{BAP}} = -2\pi\sum_{\mathbf{k}',\mathbf{q}}\delta(\varepsilon^e_{\mathbf{k}-\mathbf{q}} - \varepsilon^e_{\mathbf{k}} + \varepsilon^h_{\mathbf{k}'} - \varepsilon^h_{\mathbf{k}'-\mathbf{q}})M_\sigma(\mathbf{k}-\mathbf{q},\mathbf{k}')M_{-\sigma}(\mathbf{k},\mathbf{k}'-\mathbf{q})$$
$$\times[(1-f^h_{\mathbf{k}',\sigma})f^h_{\mathbf{k}'-\mathbf{q},-\sigma}f_{\mathbf{k},\sigma}(1-\underline{f_{\mathbf{k}-\mathbf{q},-\sigma}}) - f^h_{\mathbf{k}',\sigma}(1-f^h_{\mathbf{k}'-\mathbf{q},-\sigma})(1-\underline{f_{\mathbf{k},\sigma}})f_{\mathbf{k}-\mathbf{q},-\sigma}]$$

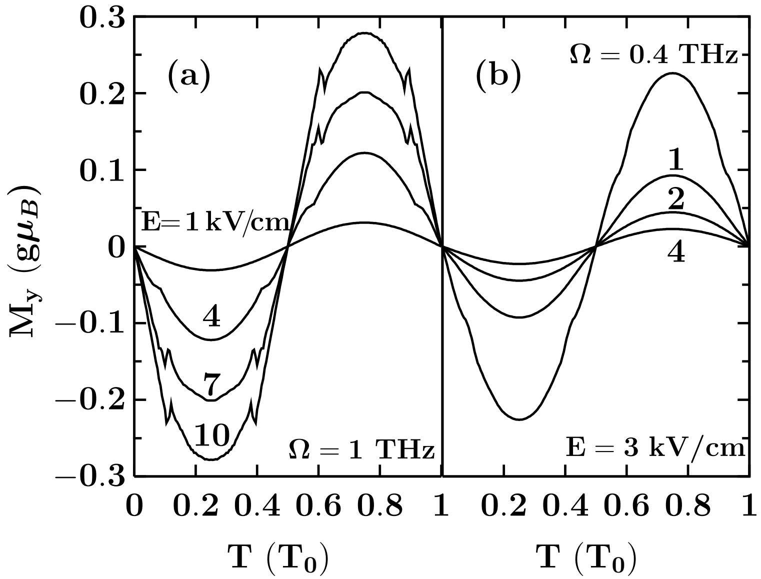




Experimental verification: [Yang *et al.*, arXiv:0902.0484]

Manipulation of Spin by Strong THz Fields

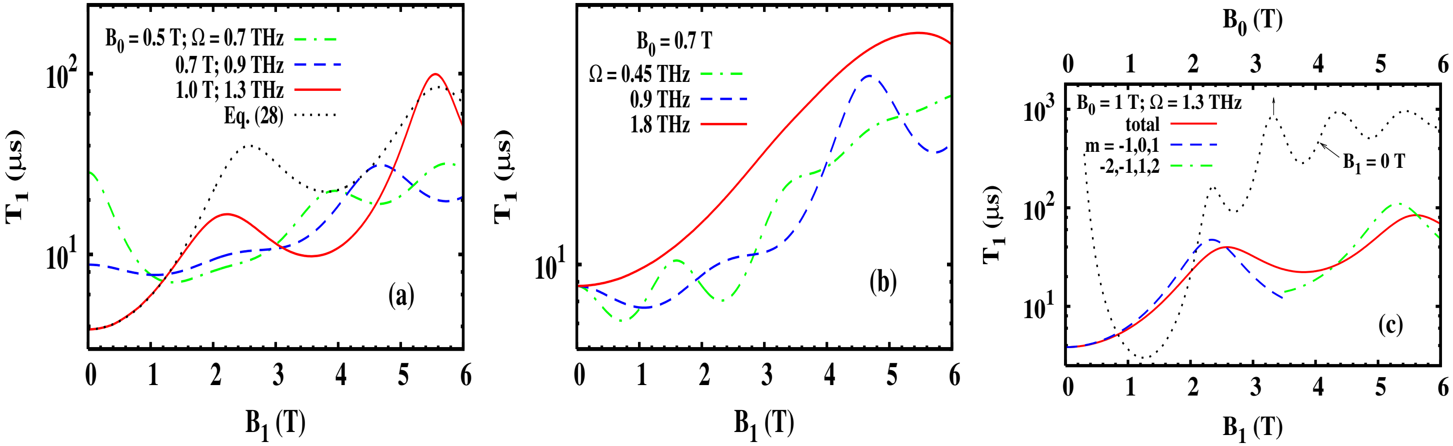
- Without dissipation



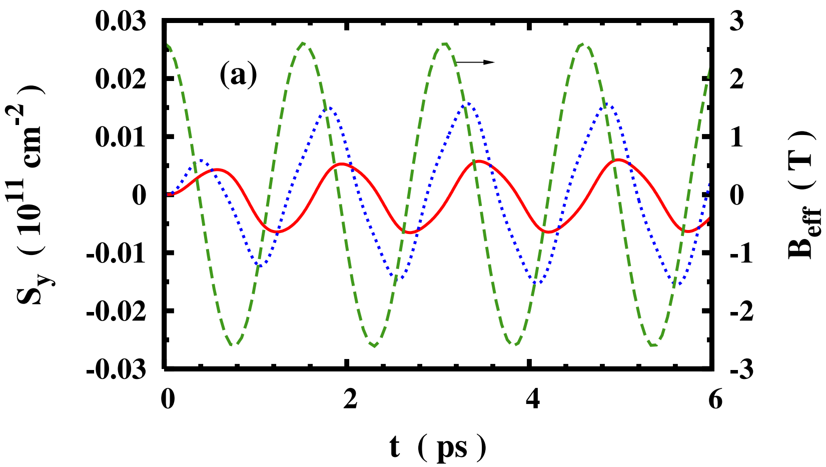
- 2DEG with Rashba SOC [Cheng and Wu, APL **86**, 032107 (2005)].

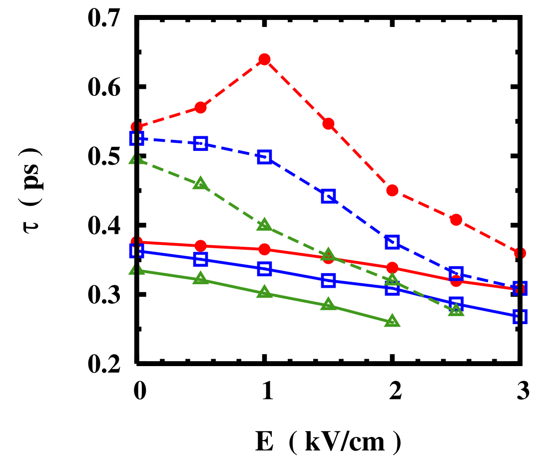
- 2DHG [Zhou, Physica E **40**, 2847 (2008)].
- QDs [Jiang, Weng, and Wu, JAP **100**, 063709 (2006)].

- With dissipation:
  - QDs [Jiang and Wu, PRB **75**, 035307 (2007)].



  - 2DEG [Jiang, Wu, and Zhou, PRB **78**, 125309 (2008)].





Quasi-Independent Electron Model

Most of the theoretical works are based on quasi-independent model and focused on the diffusive transport regime [Schmidt *et. al.*, PRB **62**, R4790 (2000); Žutić *et al.*, PRB **64**, 121201 (2001); PRL **88**, 066603 (2002)]:

Diffusive transport equation

$$\frac{\partial n_\sigma(\mathbf{R},t)}{\partial t} - \frac{1}{e}\nabla\cdot\mathbf{J}_\sigma(\mathbf{R},t) = -\frac{n_\sigma(\mathbf{R},t)-n_0(\mathbf{R},t)}{\tau_s}$$

$\mathbf{J}_\sigma(\mathbf{R},t) = n_\sigma(\mathbf{R},t)e\mu\mathbf{E} + D\nabla n_\sigma(\mathbf{R},t)$ μ — electron mobility

D — electron diffusion constant τ_s — spin relaxation time

Stationary solution for $E=0$:

$\Delta n(x) = \Delta n(0)e^{-x/\lambda_s}$;$\lambda_s = \sqrt{D\tau_s}$

Whether the quasi-independent electron model is adequately account for the experimental results or many-body process is important?

Kinetic Spin Bloch Equations

[Weng and Wu, PRB **66**, 235109 (2002); JAP **93**, 410 (2003)]

$$\frac{\partial \rho(\mathbf{R},\mathbf{k},t)}{\partial t} - \frac{1}{2}\left\{\nabla_{\mathbf{R}}\bar{\varepsilon}(\mathbf{R},\mathbf{k},t), \nabla_{\mathbf{k}}\rho(\mathbf{R},\mathbf{k},t)\right\} + \frac{1}{2}\left\{\nabla_{\mathbf{k}}\bar{\varepsilon}(\mathbf{R},\mathbf{k},t), \nabla_{\mathbf{R}}\rho(\mathbf{R},\mathbf{k},t)\right\} = \left.\frac{\partial \rho(\mathbf{R},\mathbf{k},t)}{\partial t}\right|_c + \left.\frac{\partial \rho(\mathbf{R},\mathbf{k},t)}{\partial t}\right|_s .$$

$\rho_{\sigma\sigma}(\mathbf{R},\mathbf{k},t) = f_\sigma(\mathbf{R},\mathbf{k},t)$ — distribution function

$\rho_{\sigma-\sigma}(\mathbf{R},\mathbf{k},t)$ — spin coherence

$$\bar{\varepsilon}_{\sigma\sigma'}(\mathbf{R},\mathbf{k},t) = \frac{k^2}{2m^*}\delta_{\sigma\sigma'} + \left[g\mu_B\mathbf{B} + \mathbf{\Omega}(\mathbf{k})\right]\cdot\frac{\boldsymbol{\sigma}_{\sigma\sigma'}}{2} - e\psi(\mathbf{R},t) + \Sigma_{\sigma\sigma'}(\mathbf{R},\mathbf{k},t)$$

Scattering free solution:

$$\rho_{\mathbf{k}}(x) = e^{-\frac{im^*}{2}x\boldsymbol{\sigma}\cdot[g\mu_B\mathbf{B}+\mathbf{\Omega}(\mathbf{k})]/k_x}\rho_{\mathbf{k}}(x=0)e^{\frac{im^*}{2}x\boldsymbol{\sigma}\cdot[g\mu_B\mathbf{B}+\mathbf{\Omega}(\mathbf{k})]/k_x}$$

Inhomogeneous Broadening (Transport): $[g\mu_B\mathbf{B} + \mathbf{\Omega}(\mathbf{k})]/k_x$

Simplified Kinetic Equation

[Weng and Wu, PRB **66**, 235109 (2002)]

$$\frac{k_x}{m^*}\partial_x f_\sigma(x,\mathbf{k}) - g\mu_B B\,\mathrm{Im}\big[\rho_{-\sigma,\sigma}(x,\mathbf{k})\big] = 0,$$

$$\frac{k_x}{m^*}\partial_x \rho_{\sigma-\sigma}(x,\mathbf{k}) - i\frac{g\mu_B B}{2}\Delta f_\sigma(x,\mathbf{k}) = 0.$$

Boundary conditions:

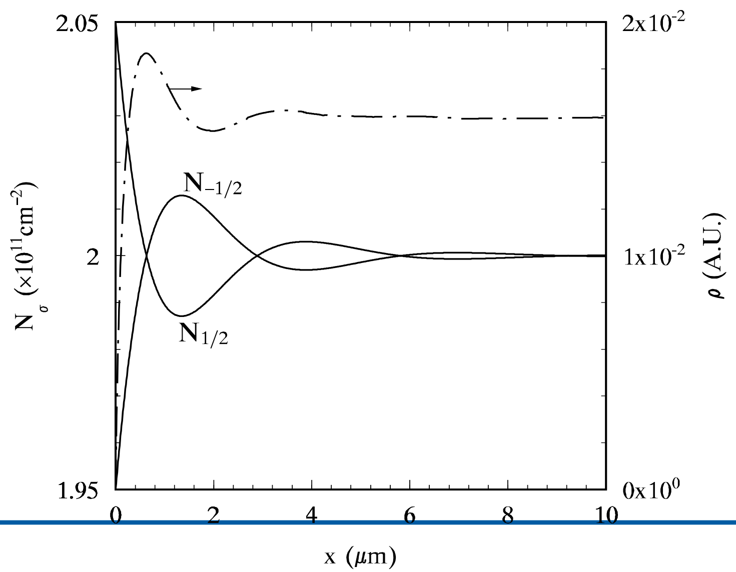
$$f_\sigma(0,\mathbf{k},t) \equiv f_\sigma^0(\mathbf{k}) = \{\exp[(\varepsilon_k - \mu_\sigma)/T] + 1\}^{-1}$$

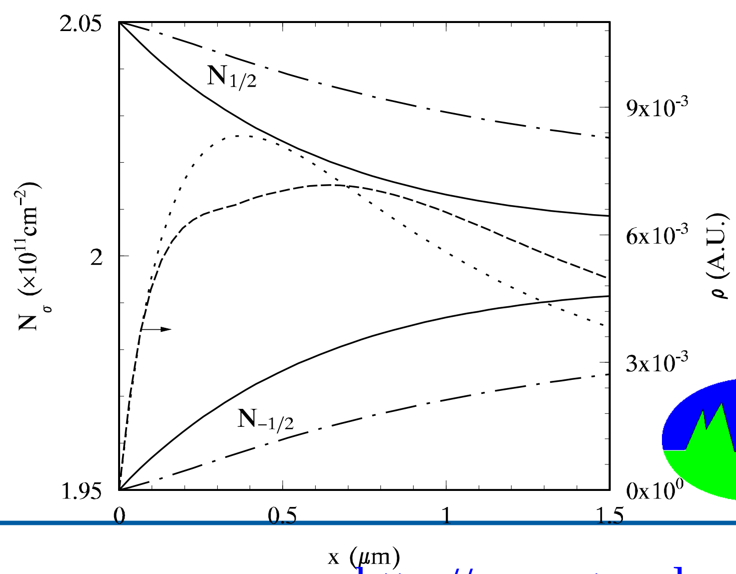
$$\rho_{\sigma-\sigma}(0,\mathbf{k},t) \equiv 0$$

Solution:

$$\Delta f_\sigma(x,\mathbf{k}) = \Delta f_\sigma^0(\mathbf{k})\cos\Big(\frac{g\mu_B B m^* x}{k_x}\Big),$$

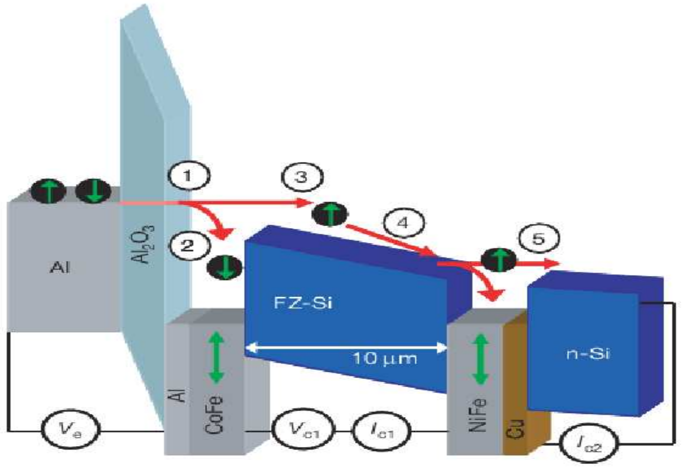
$$\rho_{\sigma-\sigma}(x,\mathbf{k}) = \frac{i}{2}\Delta f_\sigma^0(\mathbf{k})\sin\Big(\frac{g\mu_B B m^* x}{k_x}\Big).$$

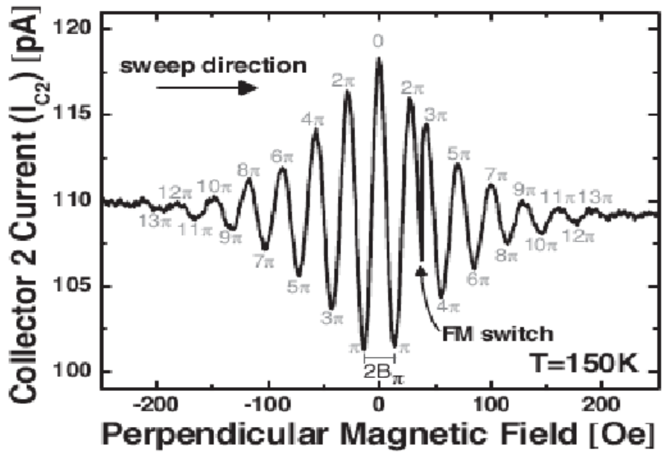




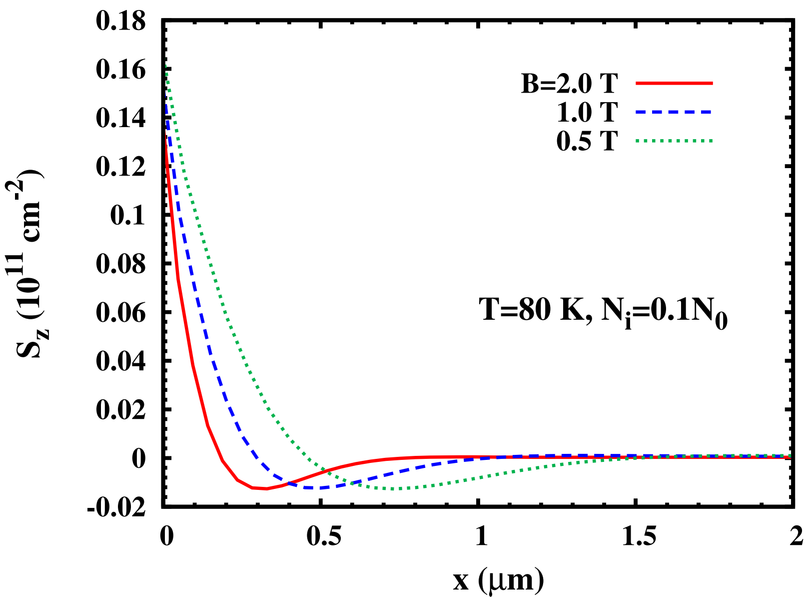
Spin Diffusion in Si/Ge Quantum Well

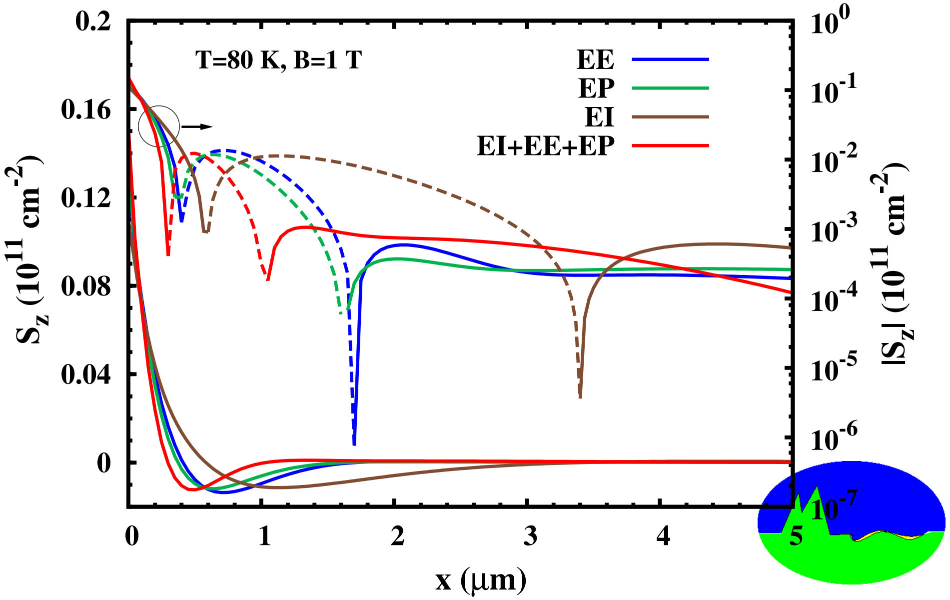
[Zhang and Wu, PRB **79**, 075303 (2009)]





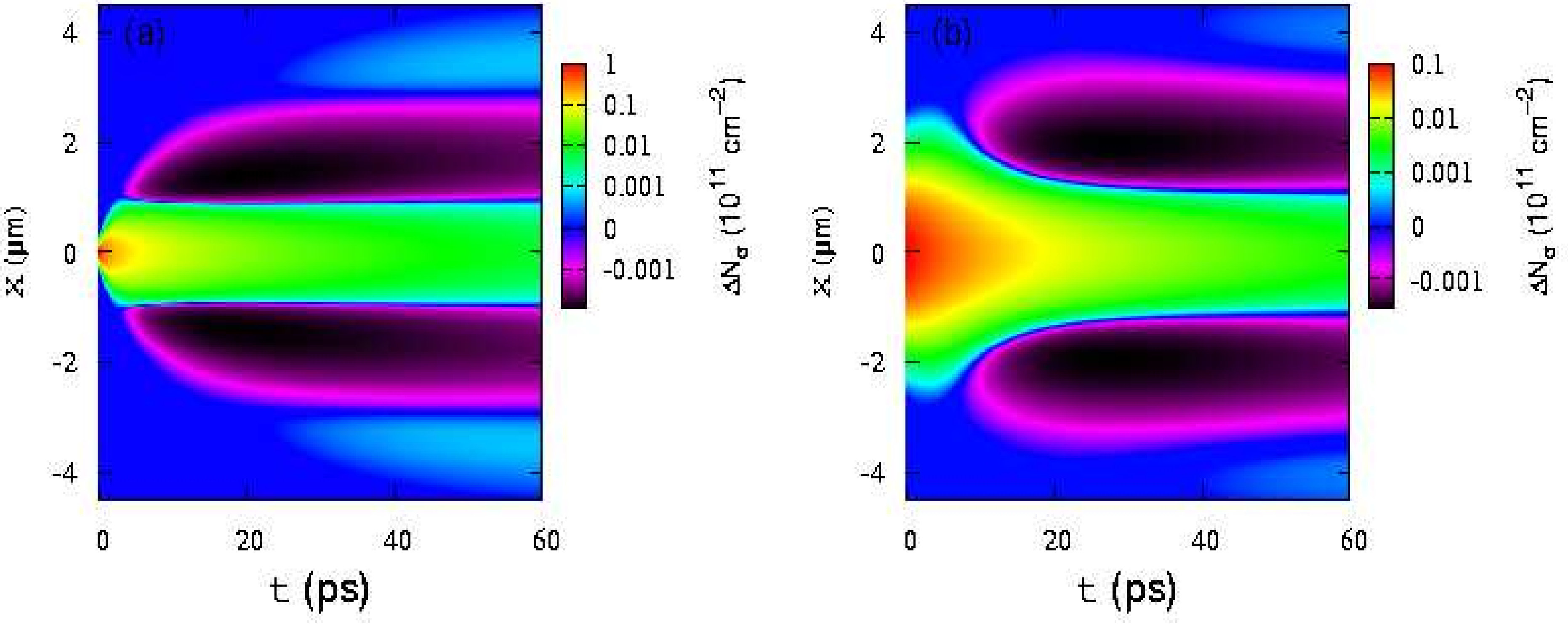
[Appelbaum *et al*., Nature **44**, 295 (2007); PRL **99**, 177209 (2007)]





Spin Oscillations along the Diffusion in the absence of Magnetic Field

[Weng and Wu, JAP **93**, 410 (2003); PRB **69**, 125310 (2004)]

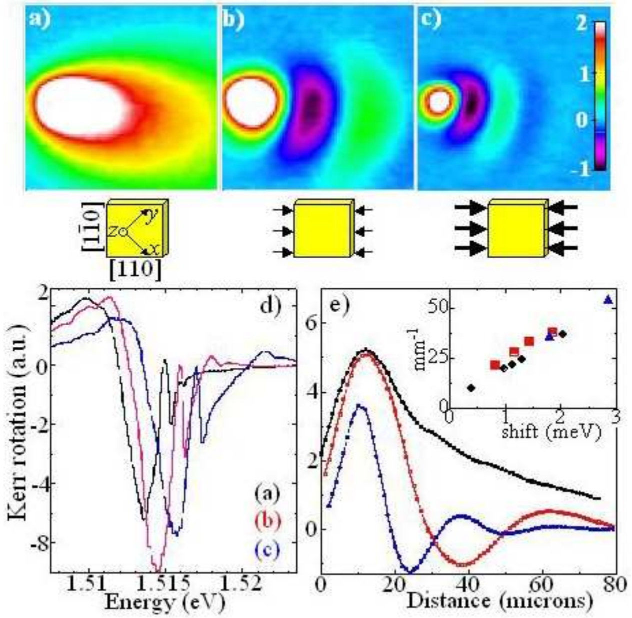


The inhomogeneous broadening [Cheng and Wu, JAP **101**, 073702 (2007)]:

$$\mathbf{\Omega}(\mathbf{k})/k_x = \gamma(-\frac{\pi^2}{a^2} - k_y^2, \frac{k_y}{k_x}(\frac{\pi^2}{a^2} - k_x^2), 0) \ .$$

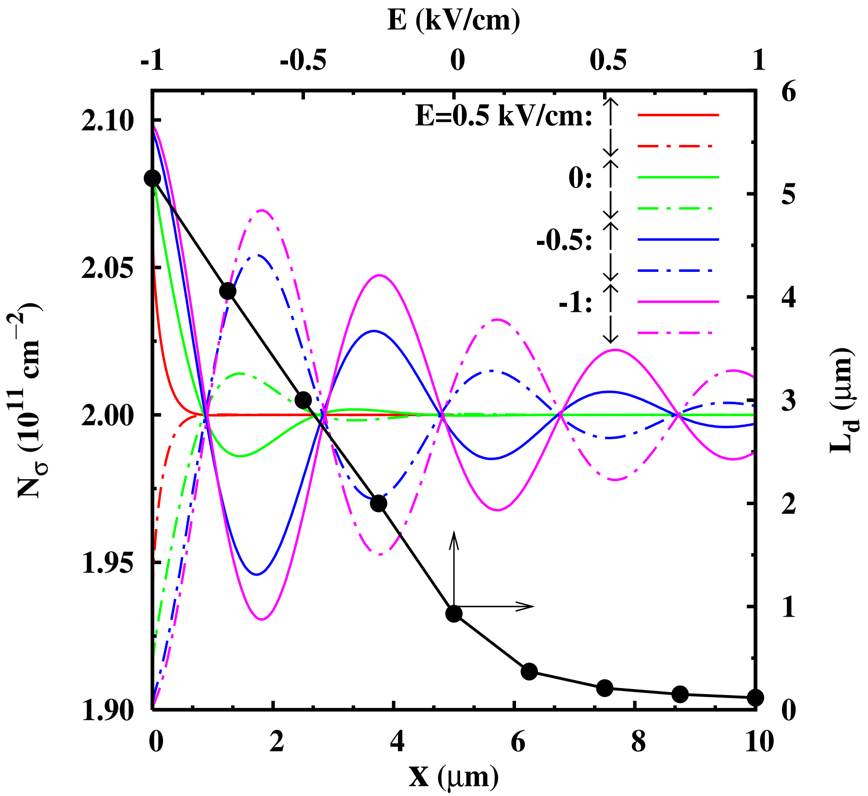
Experiment Realization

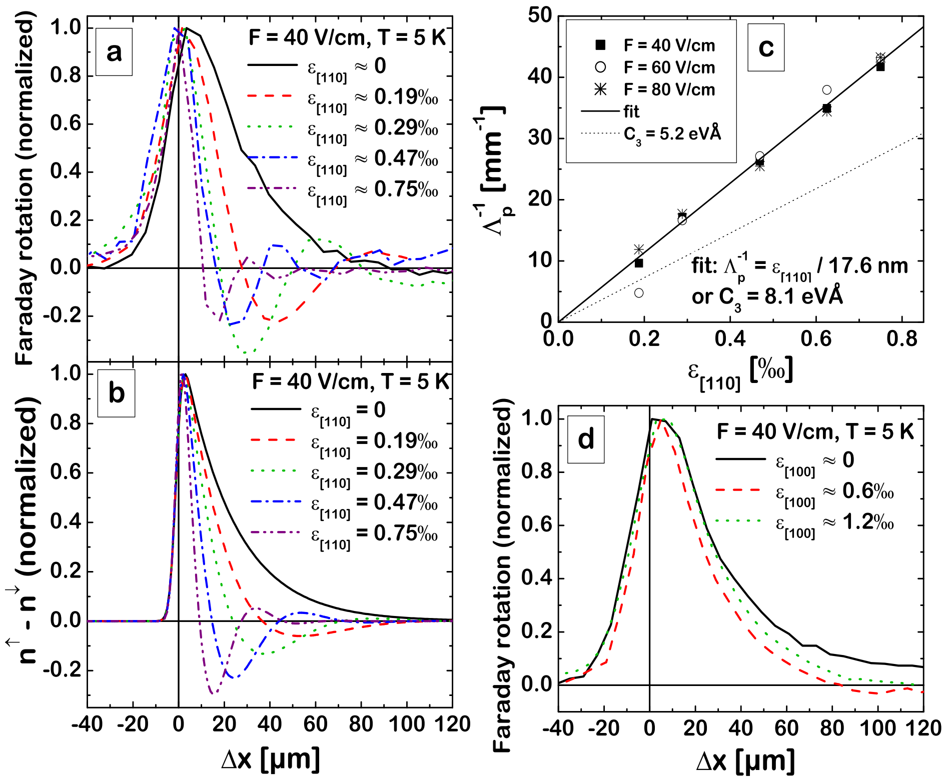
- It was originally predicted that the spin oscillation and spin reverse along the direction of spin diffusion in the absence of the applied magnetic field in quantum wells at high temperature (~ 200 K) by Weng and Wu *[J. Appl. Phys.* **93***, 410 (2003); Phys. Rev. B 69, 125310 (2004)]*;
- This behavior has been reproduced later by Monte Carlo simulations by Pershin *[Y. V. Pershin, PRB* **71***, 155317 (2005)]*;
- The above phenomena were observed by Crooker and Smith in a recent experiment at bulk GaAs at a very low temperature (4 K) *[PRL* **94***, 236601 (2005)]* .



Electric Field Dependence in the Steady State

[Cheng and Wu, JAP **101**, 073702 (07)]   [Beck *et al.*, Europhys. Lett. **75**, 597 (06)]

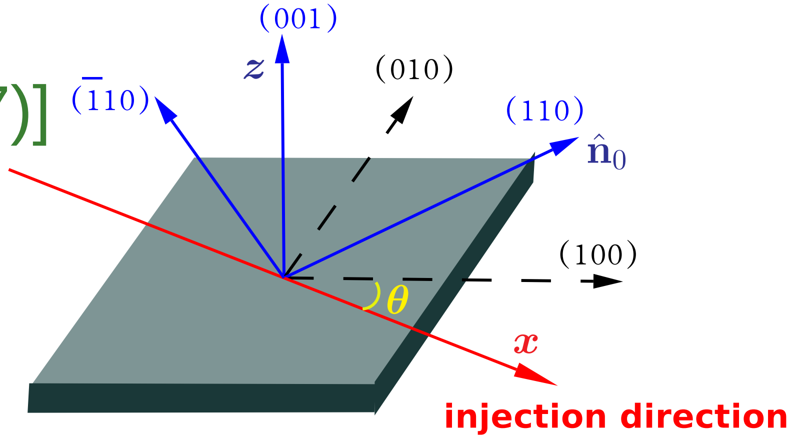




$$\mathbf{\Omega}(\mathbf{k})/k_x = \gamma\left(-\frac{\pi^2}{a^2} - k_y^2, \frac{k_y}{k_x}\left(\frac{\pi^2}{a^2} - k_x^2\right), 0\right) .$$

Anisotropy in Spin Transport with Rashba and Dresselhaus Coupling

[Cheng amd Wu, PRB **75**, 205328 (2007)]



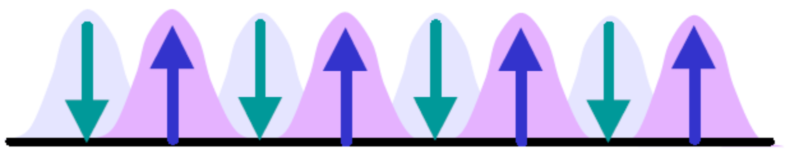
$$\frac{\mathbf{\Omega}(\mathbf{k})}{k_x} = \frac{m^*}{2\hbar^2}\left\{2\beta\left(\sin(\theta-\frac{\pi}{4})+\cos(\theta-\frac{\pi}{4})\frac{k_y}{k_x}\right)\hat{\mathbf{n}}_0 + \gamma(\frac{k_x^2-k_y^2}{2}\sin 2\theta + k_x k_y \cos 2\theta)\begin{pmatrix} k_y/k_x \\ -1 \\ 0 \end{pmatrix}\right\}.$$

Without cubic Dresselhaus term, infinite injection length is obtained when

- Spin Injection direction is along (–110), *i.e.*, $\theta = 3\pi/4$, regardless of the spin polarization direction
- Spin Polarization is along $\hat{\mathrm{n}}_0$, *i.e.*, (110), regardless of the direction of spin injection

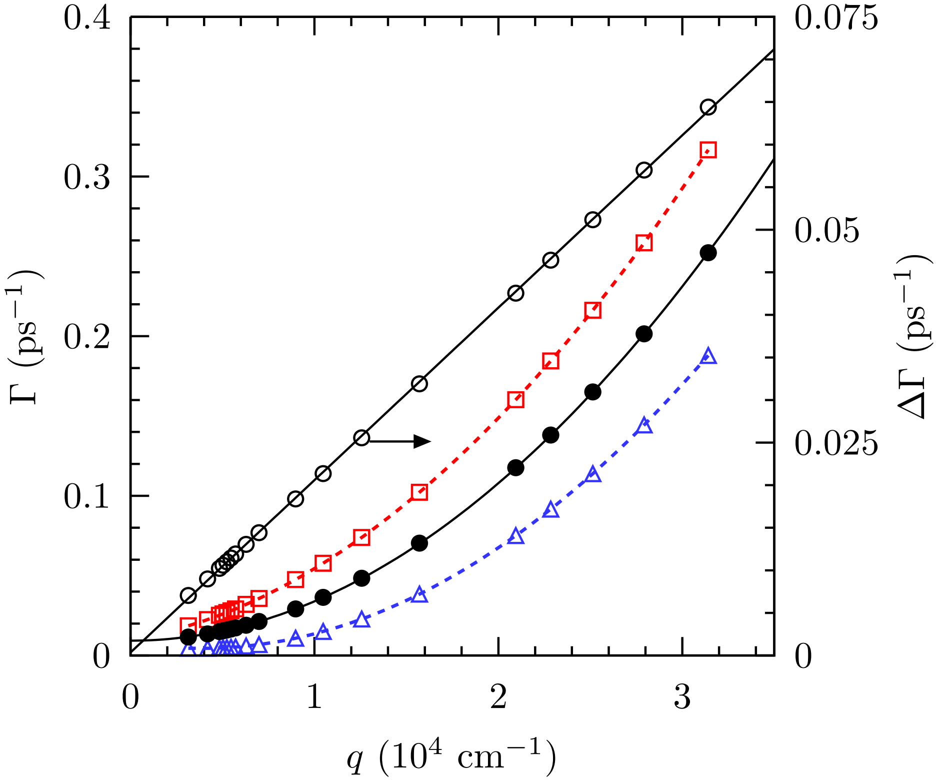
Spin Relaxation with Transient Spin Grating

[Weng, Wu, and Cui, JAP **103**, 063714 (2008)]



[Cameron *et al.*, PRL **76**, 4793 (96);
Weber *et al.*, Nature **473**, 1330 (05)]

$$\Gamma_q = 1/\tau_q = D_s q^2 + 1/\tau_s \qquad L_s = \sqrt{D_s \tau_s}$$



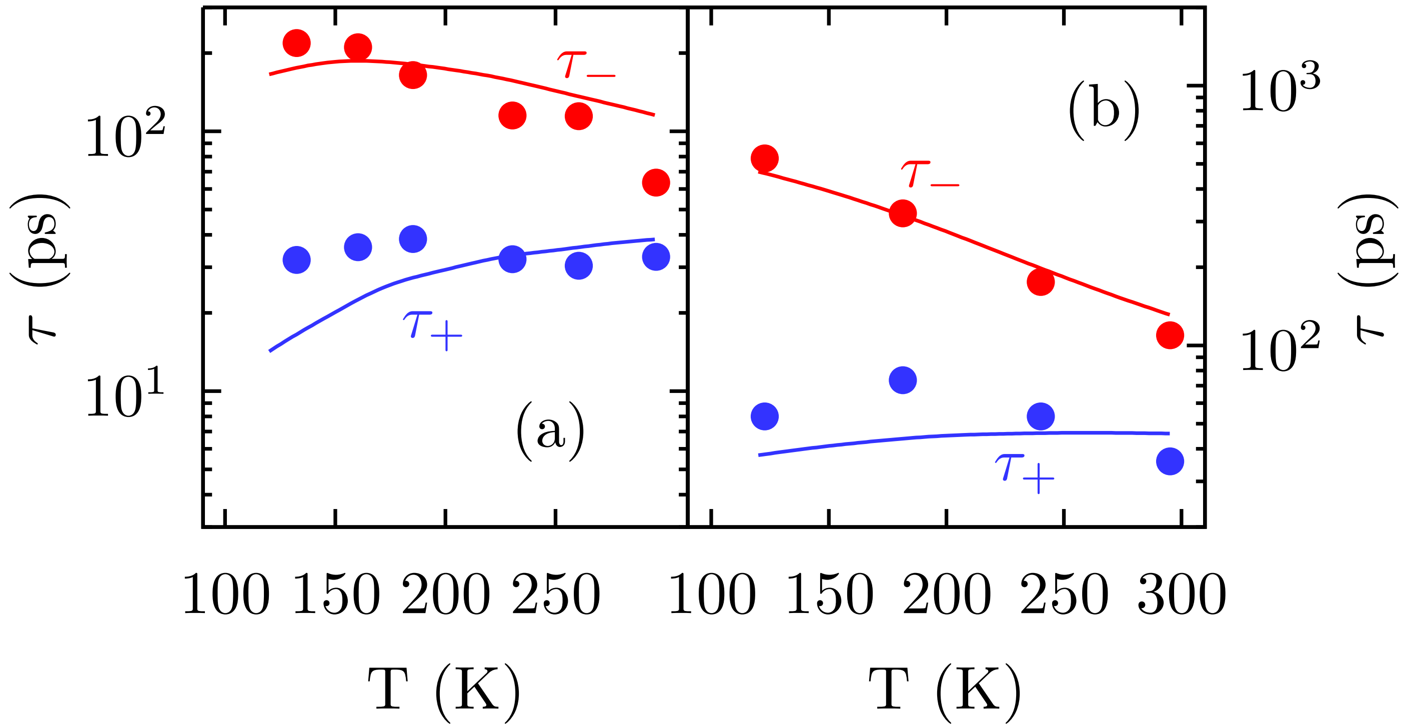
$$\Gamma = (\Gamma_+ + \Gamma_-)/2 = D_s q^2 + 1/\tau_s'$$

$$\Delta\Gamma = (\Gamma_+ - \Gamma_-)/2 = cq + d$$

$$L_s = 2D_s/\sqrt{|c^2 - 4D_s(1/\tau_s' - d)|}$$

$$1/\tau_s' = [1/(2\tau_s) + 1/\tau_s]/2 = 3/(4\tau_s)$$

Comparison with Experiments

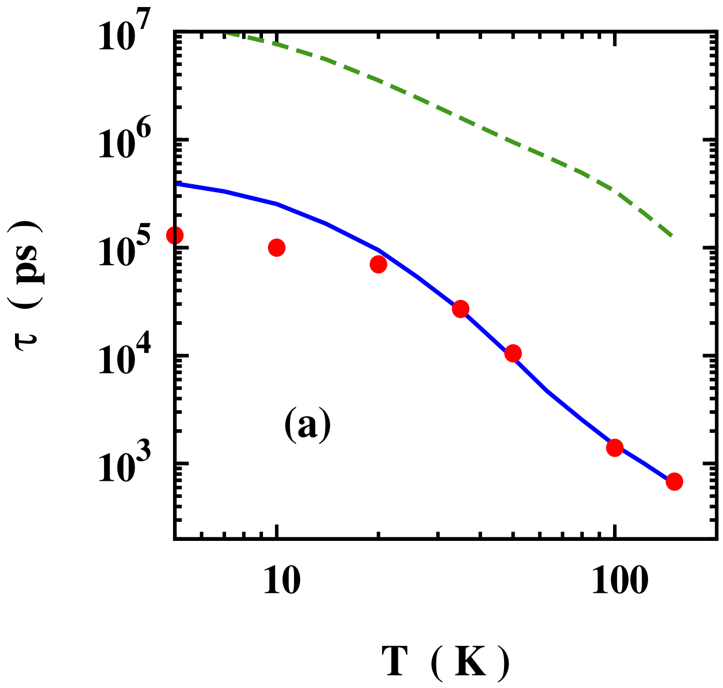


[Weber *et al.*, PRL **98**, 076604 (2007)]

- **Bulk III-V Semiconductors**

Comparison with Experiments: n-type GaAs

[Jiang and Wu, arXiv:0812.0862]



[Kikkawa and Awschalom, PRL **80**, 4313 (98)]

n-GaAs $\gamma_{\rm D} = 8.2$ eV·Å^3

$N_i = n_e = 10^{16}$ cm^{-3}

●: Experimental data

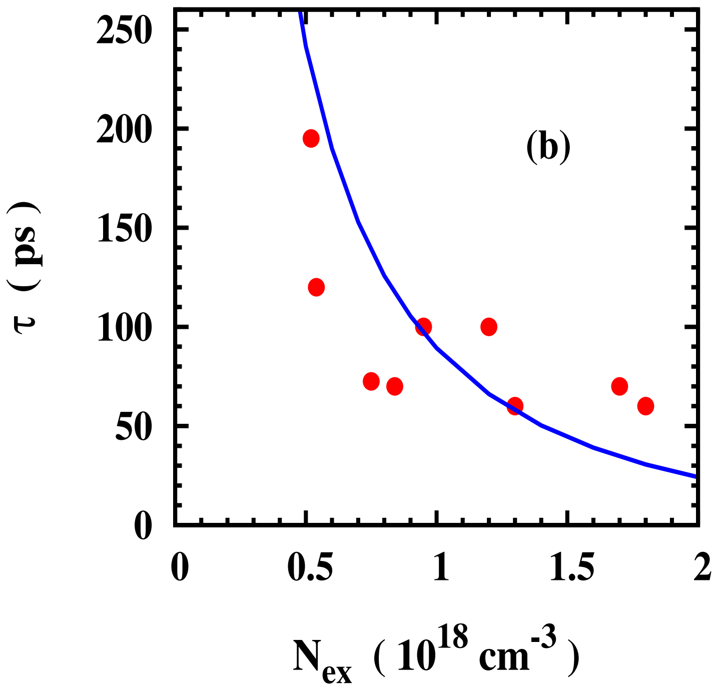
Blue curve: DP spin relaxation time from our calculation

Green curve: EY spin relaxation time from our calculation

- Our calculation agrees well with experiments in the metallic regime.
- Deviation in low temperature regime is due to the localization of electrons.

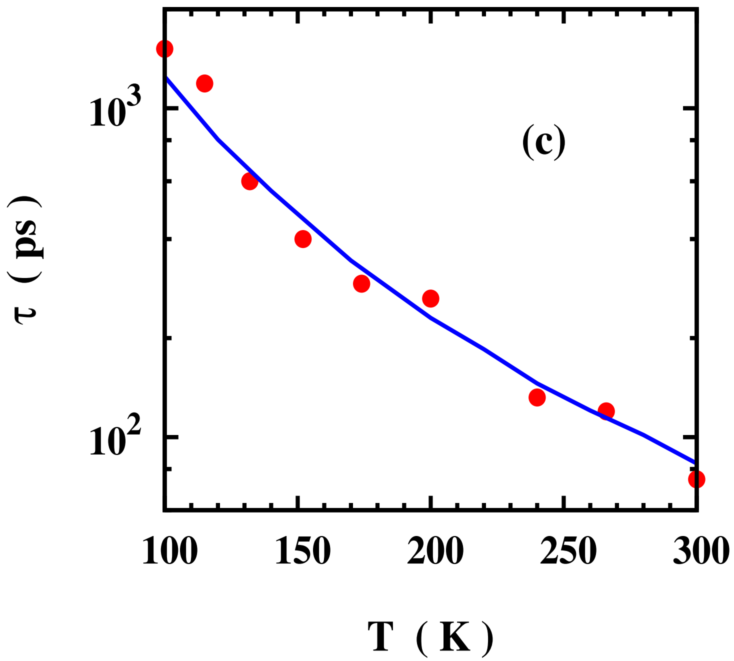
Comparison with Experiments: p-type GaAs

[Jiang and Wu, arXiv:0812.0862]



$n_i = n_h = 6 \times 10^{16}$ cm^{-3} and $T = 100$ K

[Seymour *et al.*, PRB **24**, 3623 (81)]

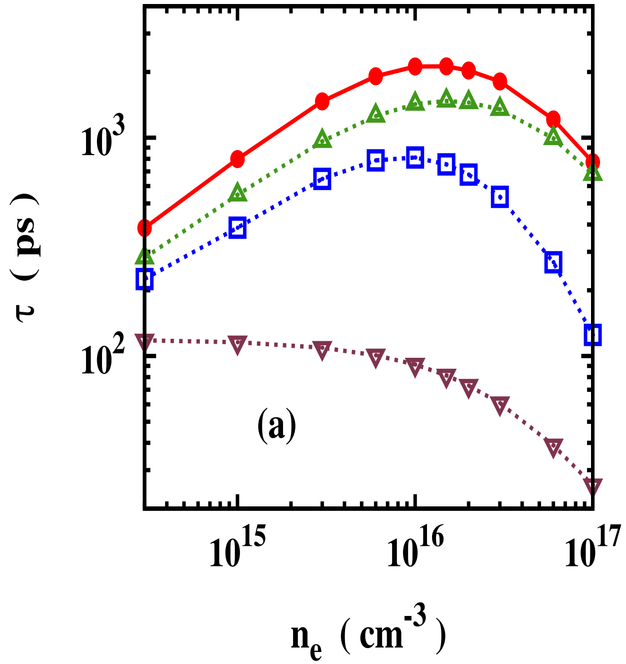


$n_i = n_h = 1.6 \times 10^{16}$ cm^{-3} and $N_{\rm ex} = 10^{14}$ cm^{-3}

[Zerrouati *et al.*, PRB **37**, 1334 (88)]

Prediction and Realization in n-GaAs

[Jiang and Wu, arXiv:0812.0862]

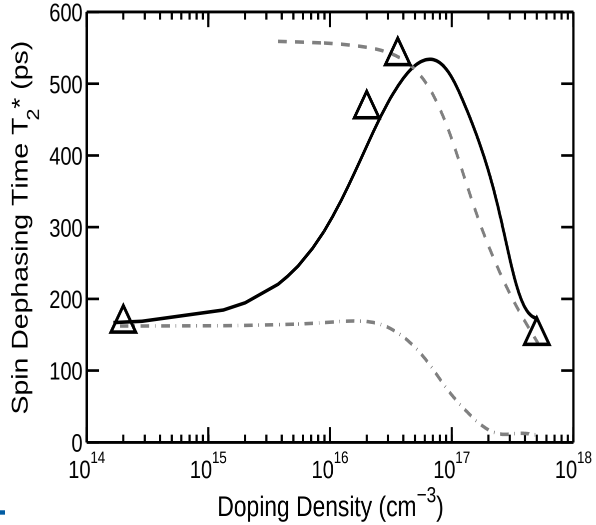


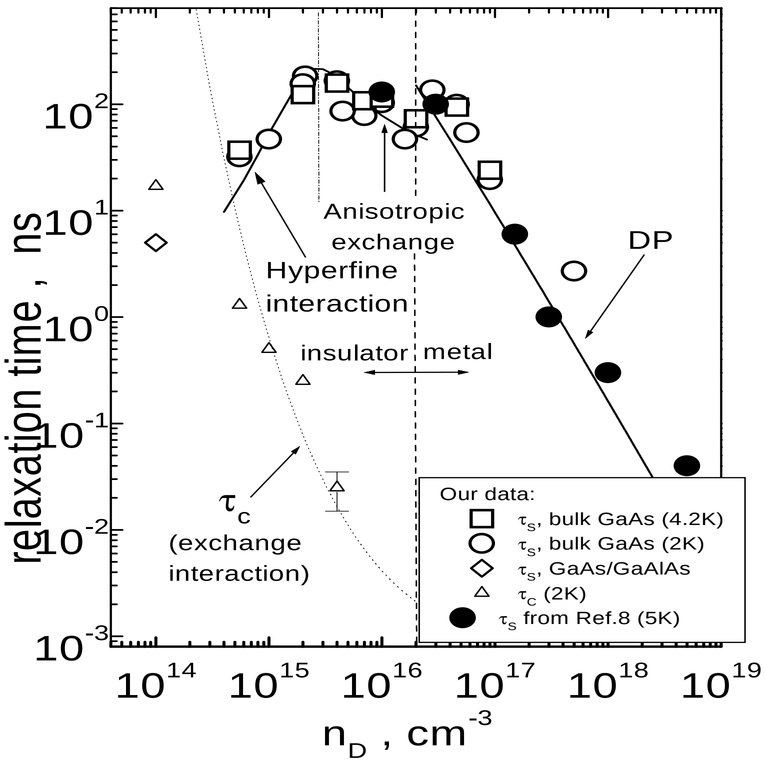
Peak in metallic regime:

Krauß et al., arXiv:0902.0270

Peak associated with Mott transition:

Dzhioev et al., PRB **66**, 245204 (02)





Previous Understandings of Spin Relaxation in Bulk III-V Semiconductors

- EY mechanism dominates at low temperature in narrow bandgap semiconductors.
- BAP mechanism dominates at low temperature in heavily p-doped semiconductors.
- DP mechanism dominates other regimes.
- Spin relaxation time decreases with temperature/density monotonically in n-type semiconductors in metallic regime.
- Spin relaxation time decreases with temperature/hole-density monotonically in p-type semiconductors in metallic regime.

Summary of our KSBE Investigation

[Jiang and Wu, arXiv:0812.0862]

- Important Predictions:
  - A peak in density dependence of spin relaxation time in metallic regime in both n-type and intrinsic semiconductors;
  - A peak in temperature dependence in intrinsic semiconductors at small spin polarization;
  - A peak in hole density dependence in p-type semiconductors due to density dependence of screening;
  - Spin lifetime increases with initial spin polarization in intrinsic semiconductors at low temperature and/or high excitation density;
  - Higher electric field always lead to shorter spin relaxation time in n-type III-V semiconductors;
- EY mechanism is found to be less important than DP mechanism, even for narrow band-gap semiconductors, such as, InSb and InAs;
- BAP mechanism is not important in intrinsic semiconductors;

- Relative importance of BAP mechanism decreases with photo-excitation density and eventually becomes negligible;
- In p-type III-V semiconductors, BAP mechanism dominates spin relaxation in low temperature regime only when photo-excitation density is low, while it is not important when photo-excitation density is sufficiently high.

Thank You!