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Full Electrical Control of the Electron Spin Relaxation in GaAs Quantum Wells

A. Balocchi,[1] Q. H. Duong,[1] P. Renucci,[1] B. L. Liu,[2]
C. Fontaine,[3] T. Amand,[1] D. Lagarde,[1] and X. Marie[1]

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[2]*Beijing National Laboratory for Condensed Matter Physics, Chinese Academy of Sciences; Beijing, China*
[3]*LAAS, CNRS, Université de Toulouse; Toulouse, France*

Journal Club, 27 September 2011

Famous Equations

- Newton's equation of motion: $\boldsymbol{F} = m\boldsymbol{a}$
- Maxwell equations:

$$\begin{aligned} \nabla \cdot \boldsymbol{E} &= \rho/\epsilon_0 \\ \nabla \cdot \boldsymbol{B} &= 0 \\ \nabla \times \boldsymbol{E} &= -\partial_t \boldsymbol{B} \\ \nabla \times \boldsymbol{B} &= \mu_0 \boldsymbol{j} + \mu_0 \epsilon_0 \partial_t \boldsymbol{E} \end{aligned}$$

- Einstein's equation: $E = \gamma m c^2$
- Schrödinger equation: $i\hbar\partial_t \left|\psi\right\rangle = H \left|\psi\right\rangle$
- Recently: New Equation!

New Equation

$$\left(\left(\frac{x}{7}\right)^2\sqrt{\frac{||x|-3|}{|x|-3}}+\left(\frac{y}{3}\right)^2\sqrt{\frac{|y+\frac{3\sqrt{33}}{7}|}{y+\frac{3\sqrt{33}}{7}}}-1\right)\cdot\left(\left|\frac{x}{2}\right|-\frac{3\sqrt{33}-7}{112}x^2-3+\sqrt{1-(||x|-2|-1)^2}-y\right)$$

$$\cdot\left(9\sqrt{\frac{|(|x|-1)(|x|-0.75)|}{(1-|x|)(|x|-0.75)}}-8|x|-y\right)\cdot\left(3|x|+0.75\sqrt{\frac{|(|x|-0.75)(|x|-0.5)|}{(0.75-|x|)(|x|-0.5)}}-y\right)$$

$$\cdot\left(2.25\sqrt{\frac{|(x-0.5)(x+0.5)|}{(0.5-x)(0.5+x)}}-y\right)\cdot\left(\frac{6\sqrt{10}}{7}+(1.5-0.5|x|)\sqrt{\frac{||x|-1|}{|x|-1}}-\frac{6\sqrt{10}}{14}\sqrt{4-(|x|-1)^2}-y\right)=0$$

New Equation

$$\left(\left(\frac{x}{7}\right)^2\sqrt{\frac{||x|-3|}{|x|-3}}+\left(\frac{y}{3}\right)^2\sqrt{\frac{\left|y+\frac{3\sqrt{33}}{7}\right|}{y+\frac{3\sqrt{33}}{7}}}-1\right)\cdot\left(\left|\frac{x}{2}\right|-\frac{3\sqrt{33}-7}{112}x^2-3+\sqrt{1-(||x|-2|-1)^2}-y\right)$$
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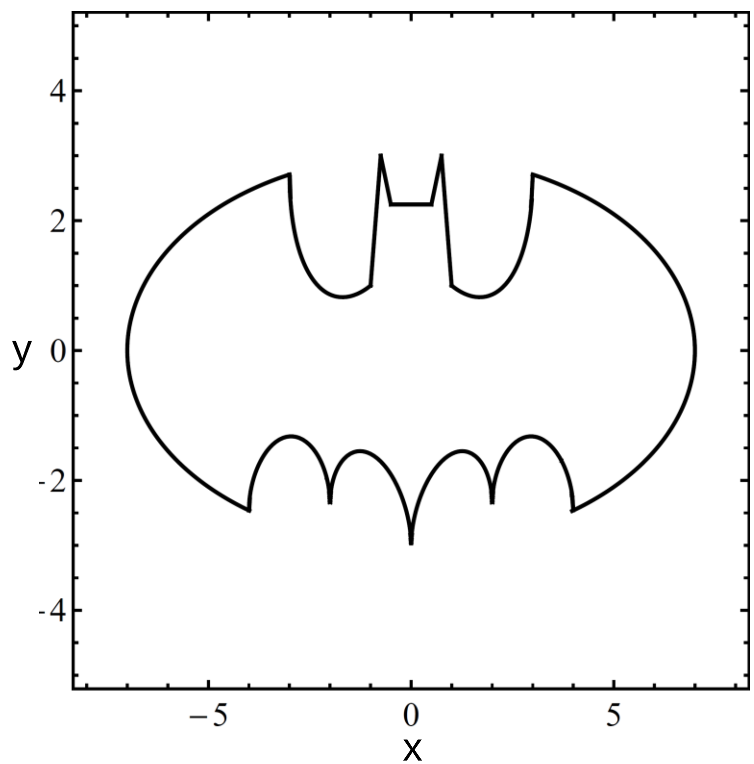
Solution:



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\end{aligned}$$

- Einstein's equation: $$E = \gamma m c^2$$

- Schrödinger equation: $$i\hbar\partial_t \left|\psi\right\rangle = H \left|\psi\right\rangle$$

- Batman's equation:
$$\begin{aligned}
&\left(\left(\frac{x}{7}\right)^2 \sqrt{\frac{||x|-3|}{|x|-3}} + \left(\frac{y}{3}\right)^2 \sqrt{\frac{\left|y+\frac{3\sqrt{33}}{7}\right|}{y+\frac{3\sqrt{33}}{7}}} - 1\right) \cdot \left(\left|\frac{x}{2}\right| - \frac{3\sqrt{33}-7}{112}x^2 - 3 + \sqrt{1-(||x|-2|-1)^2} - y\right) \\
&\cdot \left(9\sqrt{\frac{|(|x|-1)\,(|x|-0.75)|}{(1-|x|)\,(|x|-0.75)}} - 8|x| - y\right) \cdot \left(3|x| + 0.75\sqrt{\frac{|(|x|-0.75)\,(|x|-0.5)|}{(0.75-|x|)\,(|x|-0.5)}} - y\right) \\
&\cdot \left(2.25\sqrt{\frac{|(x-0.5)\,(x+0.5)|}{(0.5-x)\,(0.5+x)}} - y\right) \cdot \left(\frac{6\sqrt{10}}{7} + (1.5-0.5|x|)\sqrt{\frac{||x|-1|}{|x|-1}} - \frac{6\sqrt{10}}{14}\sqrt{4-(|x|-1)^2} - y\right) = 0
\end{aligned}$$

arXiv:1109.4897 OPERA

CERN
Geneva
Switzerland

Neutrinos

→

730 km
(2.4 ms)

Laboratori Nazionali
di Gran Sasso
Italy

arXiv:1109.4897 OPERA

CERN Geneva *Switzerland*	**Neutrinos** → 730 km (2.4 ms)	Laboratori Nazionali di Gran Sasso *Italy*

$$v = 1.0000248\ c$$

Neutrinos faster than speed of light?

Deviation from v = c:

Length: 18 m
Time: 60 ns

Press Release

Claimed accuracy:

Length: 20 cm
Time: < 10 ns

"This result comes as a complete surprise. After many months of studies and cross checks we have not found any instrumental effect that could explain the result of the measurement. While OPERA researchers will continue their studies, we are also looking forward to independent measurements to fully assess the nature of this observation."

Antonio Ereditato, University of Bern, OPERA spokesperson

"When an experiment finds an apparently unbelievable result and can find no artefact of the measurement to account for it, it is normal procedure to invite broader scrutiny, and this is exactly what the OPERA collaboration is doing (...). If this measurement is confirmed, it might change our view of physics, but we need to be sure that there are no other, more mundane, explanations."

Sergio Bertolucci, CERN Research Director

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Journal Club, 27 September 2011

Electron Spin Relaxation in Quantum Wells

Spin-Orbit Interaction (SOI)

Coupling of type $H_{SOI} = \boldsymbol{\Omega}(\mathbf{k})\cdot\boldsymbol{\sigma}$

$\boldsymbol{\sigma}$: vector of Pauli matrices for spin 1/2

$\boldsymbol{\Omega}$: “precession vector” (effective magnetic field)

$\mathbf{k}$: electron momentum in units of $\hbar$

Electron Spin Relaxation in Quantum Wells

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σ : vector of Pauli matrices for spin 1/2
Ω : "precession vector" (effective magnetic field)
k : electron momentum in units of ħ

Electron Spin Relaxation

Dominant mechanism for spin relaxation in III-V or II-VI quantum wells (QWs) is the Dyakonov-Perel mechanism:

Scattering off of dirt, dopants, phonons, defects ...

$\mathbf{k} \rightarrow \mathbf{k}'$ ⟶ $\mathbf{\Omega} \rightarrow \mathbf{\Omega}'$

Spin relaxation time τ^i_s for a spin prepared along direction i:

$$\left(\tau_s^i\right)^{-1} \propto \langle \Omega_\perp^2 \rangle$$

E.g., for spin along *z*:

$$\left(\tau_s^z\right)^{-1} \propto \langle \Omega_x^2 + \Omega_y^2 \rangle$$

Electron Spin Relaxation in Quantum Wells

The Dyakonov-Perel mechanism typically results in fast spin relaxation on the order of a few tens or hundreds of picoseconds

Longer relaxation time τ^i_s

⟷

Reduce $\langle \Omega_\perp^2 \rangle$

Spin relaxation time τ^i_s for a spin prepared along direction i:

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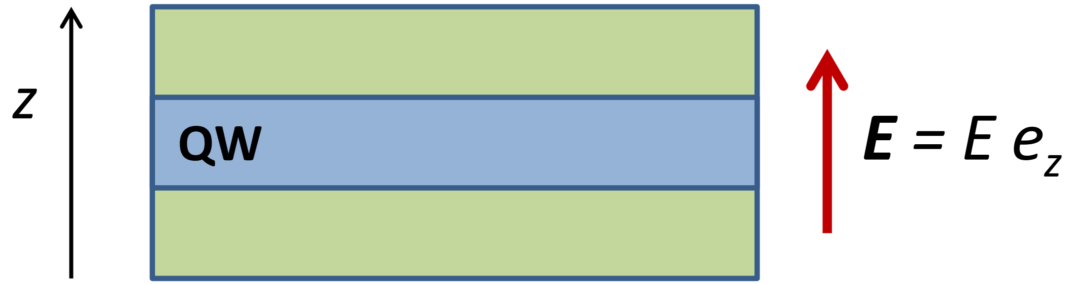
Rashba SOI



Rashba SOI arises from structural inversion asymmetry (SIA)

$$\boldsymbol{\Omega}^{\mathrm{3D}}_{\mathrm{SIA}}(\boldsymbol{k}) \propto \boldsymbol{k} \times \boldsymbol{E}$$

For an electric field applied along the *z* axis (growth axis):

$$\boldsymbol{\Omega}_{\mathrm{SIA}}(\boldsymbol{k}_{\|}) = \frac{\alpha}{\hbar}(k_y, -k_x, 0) \qquad \alpha = aE$$

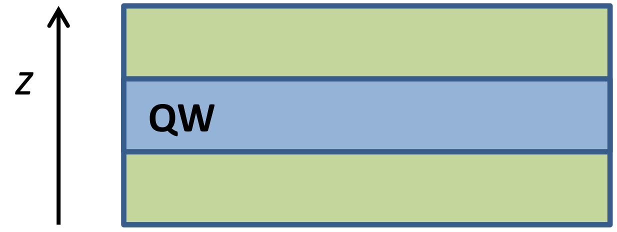
Dresselhaus SOI

Dresselhaus SOI arises from bulk inversion asymmetry (BIA)

$$H^{3D}_{BIA}(\boldsymbol{k}) \propto (k_2^2 - k_3^2)k_1\sigma_1 + (k_3^2 - k_1^2)k_2\sigma_2 + (k_1^2 - k_2^2)k_3\sigma_3$$

1, 2, 3: main crystallographic axes

→ In contrast to Rashba SOI, the Dresselhaus term depends on the growth direction of the quantum well!



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1, 2, 3: main crystallographic axes

⟶ In contrast to Rashba SOI, the Dresselhaus term depends on the growth direction of the quantum well!

Effective QW Hamiltonian:

a) Rotate bulk term

b) Substitute $k_z^2 \rightarrow \langle k_z^2 \rangle$

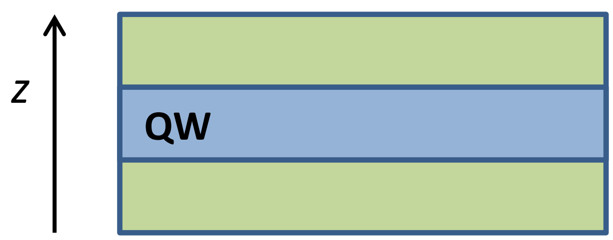
$k_z, k_z^3 \rightarrow \langle k_z \rangle = \langle k_z^3 \rangle = 0$

c) Omit cubic terms in the transverse motion, $\langle k_z^2 \rangle > k_x^2,\, k_y^2$

$$\boldsymbol{\Omega}_{\mathrm{BIA}}(\boldsymbol{k}_{\|}) = \frac{\gamma}{\hbar}\langle k_z^2\rangle(-k_x, k_y, 0) \quad \text{if } \mathbf{z} \parallel [001],$$

$$\boldsymbol{\Omega}_{\mathrm{BIA}}(\boldsymbol{k}_{\|}) = \frac{\gamma}{2\hbar}\langle k_z^2\rangle(0, 0, k_y) \quad \text{if } \mathbf{z} \parallel [110],$$

$$\boldsymbol{\Omega}_{\mathrm{BIA}}(\boldsymbol{k}_{\|}) = \frac{2\gamma}{\hbar\sqrt{3}}\langle k_z^2\rangle(k_y, -k_x, 0) \quad \text{if } \mathbf{z} \parallel [111]$$



Rashba & Dresselhaus SOI

Rashba: $$\mathbf{\Omega}_{\text{SIA}}(\boldsymbol{k}_{\|}) = \frac{\alpha}{\hbar}(k_y, -k_x, 0)$$ $$\alpha = aE$$

Dresselhaus:

$$\mathbf{\Omega}_{\text{BIA}}(\boldsymbol{k}_{\|}) = \frac{\gamma}{\hbar}\langle k_z^2\rangle(-k_x, k_y, 0) \quad \text{if } \mathbf{z} \parallel [001],$$

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Recap:

Longer relaxation time τ^i_s

⟷

Reduce $\langle \Omega_\perp^2 \rangle$

Rashba & Dresselhaus SOI, [001]

Rashba: $$\boldsymbol{\Omega}_{\rm SIA}(\boldsymbol{k}_{\|}) = \frac{\alpha}{\hbar}(k_y, -k_x, 0) \qquad \alpha = aE$$

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$$\alpha = \gamma\langle k_z^2\rangle \quad \rightarrow \quad \boldsymbol{\Omega}(\boldsymbol{k}_{\|}) = \boldsymbol{\Omega}_{\rm SIA}(\boldsymbol{k}_{\|}) + \boldsymbol{\Omega}_{\rm BIA}(\boldsymbol{k}_{\|}) = \frac{\alpha}{\hbar}(k_y - k_x)(1,1,0)$$ Long $\tau_s^{(x+y)}$

$$\alpha = -\gamma\langle k_z^2\rangle \quad \rightarrow \quad \boldsymbol{\Omega}(\boldsymbol{k}_{\|}) = \boldsymbol{\Omega}_{\rm SIA}(\boldsymbol{k}_{\|}) + \boldsymbol{\Omega}_{\rm BIA}(\boldsymbol{k}_{\|}) = \frac{\alpha}{\hbar}(k_y + k_x)(1,-1,0)$$ Long $\tau_s^{(x-y)}$

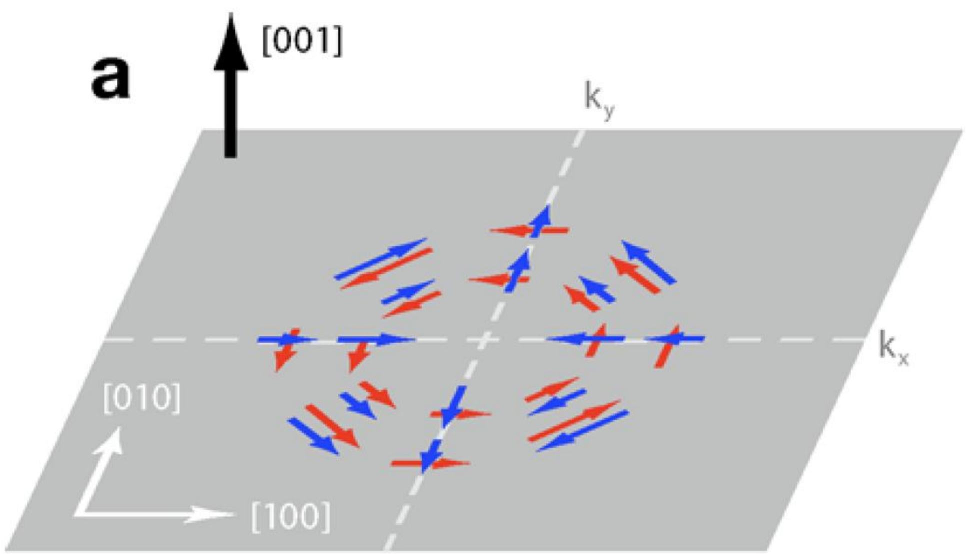

Figure from Viewpoint by M. E. Flatté

Rashba & Dresselhaus SOI, [110]

Rashba: $$\boldsymbol{\Omega}_{\mathrm{SIA}}(\boldsymbol{k}_{\|}) = \frac{\alpha}{\hbar}(k_y, -k_x, 0) \qquad \alpha = aE$$

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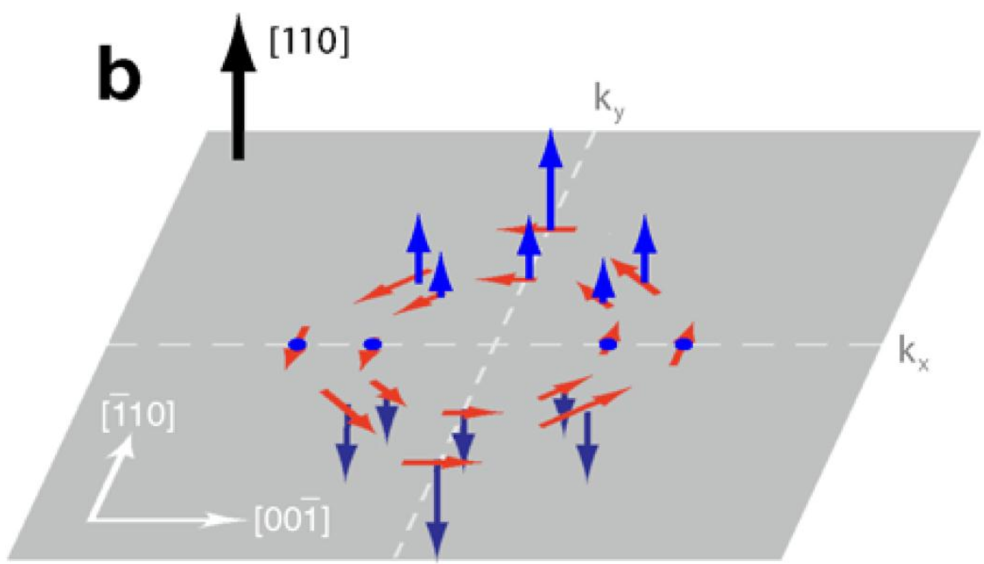
$$\alpha = E = 0 \quad \rightarrow \quad \boldsymbol{\Omega}(\boldsymbol{k}_{\|}) = \boldsymbol{\Omega}_{\mathrm{BIA}}(\boldsymbol{k}_{\|}) = \frac{\gamma}{2\hbar}\langle k_z^2\rangle k_y(0,0,1)$$

Long τ_s^z



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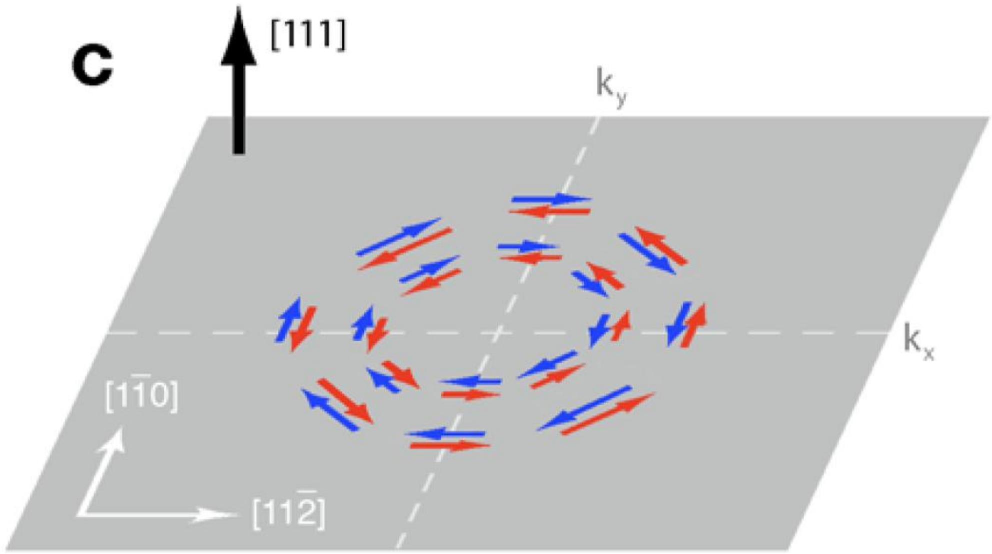
$$\alpha = -\frac{2\gamma}{\sqrt{3}}\langle k_z^2\rangle \quad \rightarrow \quad \boldsymbol{\Omega}(\boldsymbol{k}_{\|}) = \boldsymbol{\Omega}_{\text{SIA}}(\boldsymbol{k}_{\|}) + \boldsymbol{\Omega}_{\text{BIA}}(\boldsymbol{k}_{\|}) = 0$$

Long τ_s^x, τ_s^y, τ_s^z



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$\alpha = -\frac{2\gamma}{\sqrt{3}}\langle k_z^2\rangle \rightarrow \boldsymbol{\Omega}(\boldsymbol{k}_{\|}) = \boldsymbol{\Omega}_{\text{SIA}}(\boldsymbol{k}_{\|}) + \boldsymbol{\Omega}_{\text{BIA}}(\boldsymbol{k}_{\|}) = 0$ Long τ_s^x, τ_s^y, τ_s^z

Simultaneous suppression of Dyakonov-Perel relaxation for all spin orientations

So far not yet evidenced experimentally

Experimental Setup

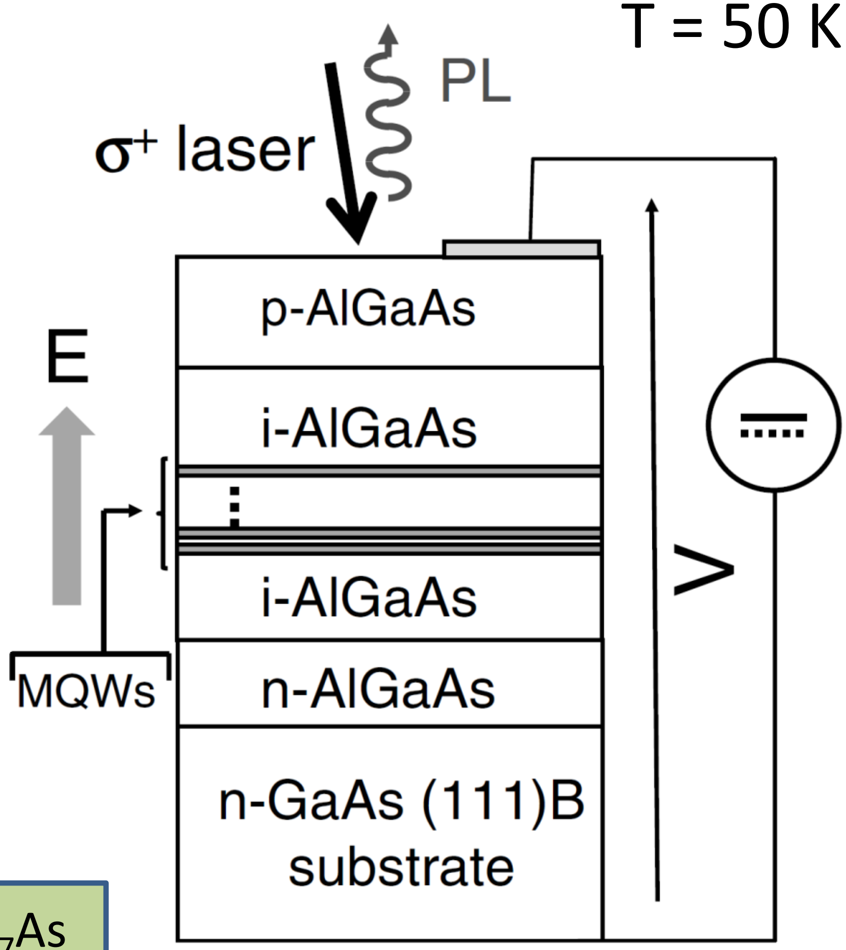
3 Samples:

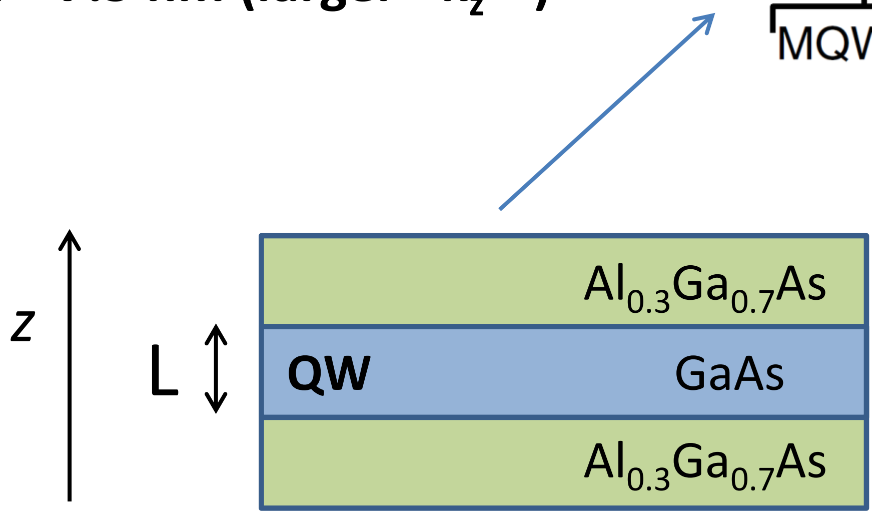
I) P-I-N
L = 15 nm

II) N-I-P (opposite el. field)
L = 15 nm

III) P-I-N
L = 7.5 nm (larger $\langle k_z^2 \rangle$)

T = 50 K



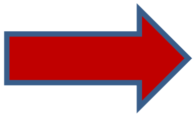


Heterostructure leads to built-in electric field of ~ 20 kV/cm

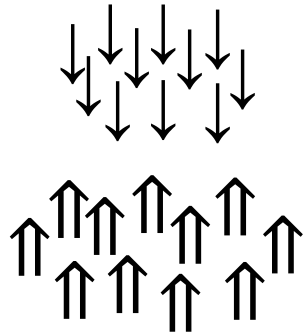
Excitation & Measurement

Excitation (qualitatively)

σ+ pulse

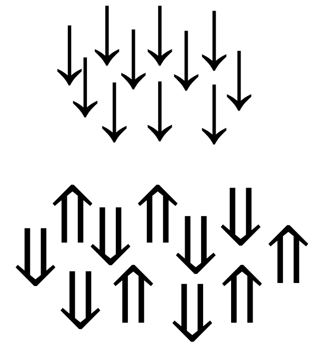


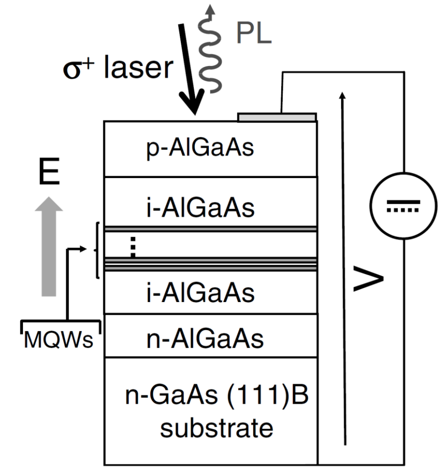
1.5 ps
1.56 eV



Very fast hole spin relaxation

~ 1 ps





Emission

$|\Uparrow\downarrow\rangle \longrightarrow$ σ+ photon

$|\Downarrow\uparrow\rangle \longrightarrow$ σ- photon

Measurement

$$P_c = \frac{I(\sigma^+) - I(\sigma^-)}{I(\sigma^+) + I(\sigma^-)}$$

Degree of circular polarization

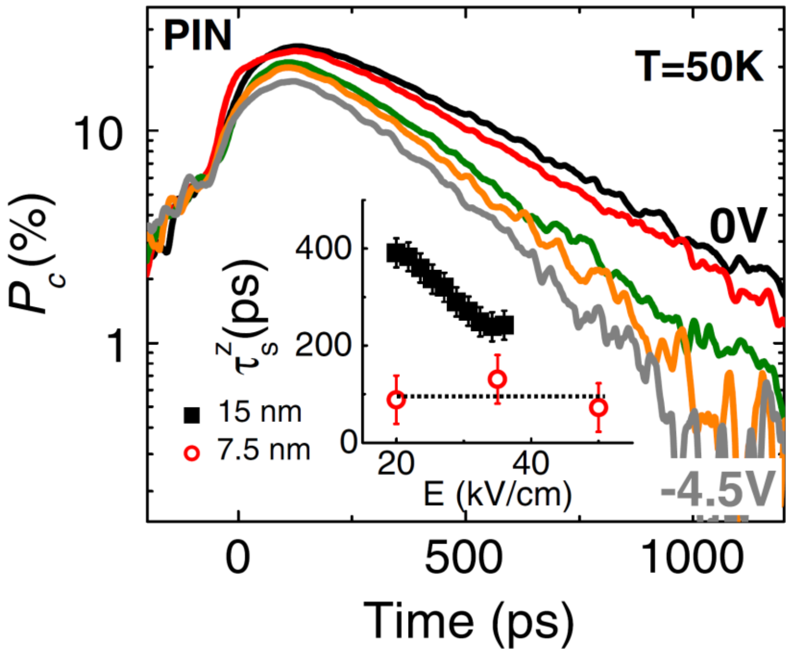
Direct probe of the QW electron spin dynamics

Experimental Results: τ_s^z

Electric field in the QW determined from measurements of the quantum confined Stark effect

<u>Samples I + III</u>

<u>P-I-N</u>



<u>L = 15 nm:</u>

Increasing the electric field <u>reduces</u> τ_s^z from 400 ps to 200 ps

<u>L = 7.5 nm:</u>

Dresselhaus term >> Rashba term

Experimental Results: τ_s^z

Electric field in the QW determined from measurements of the quantum confined Stark effect

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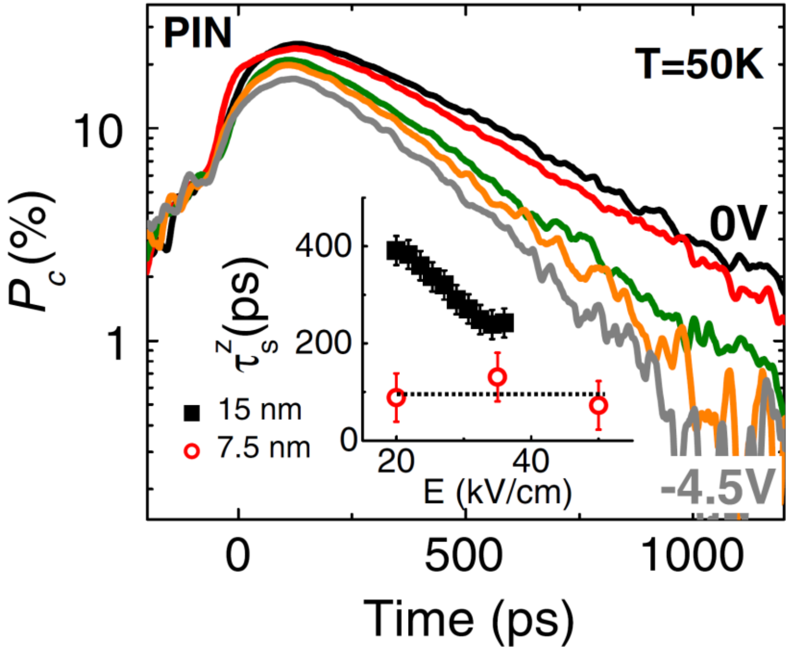

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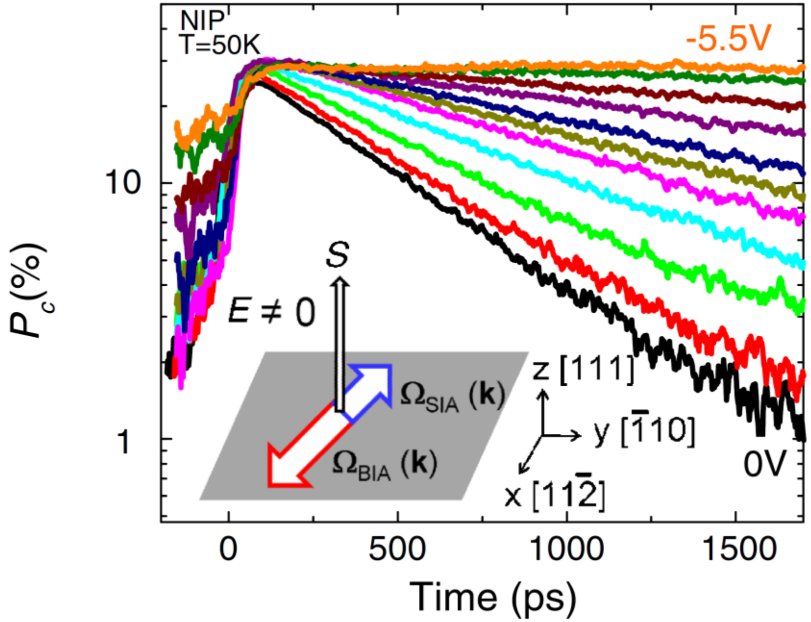
Sample II

N-I-P



With stronger electric field, τ_s^z increases from 500 ps to 30 ns

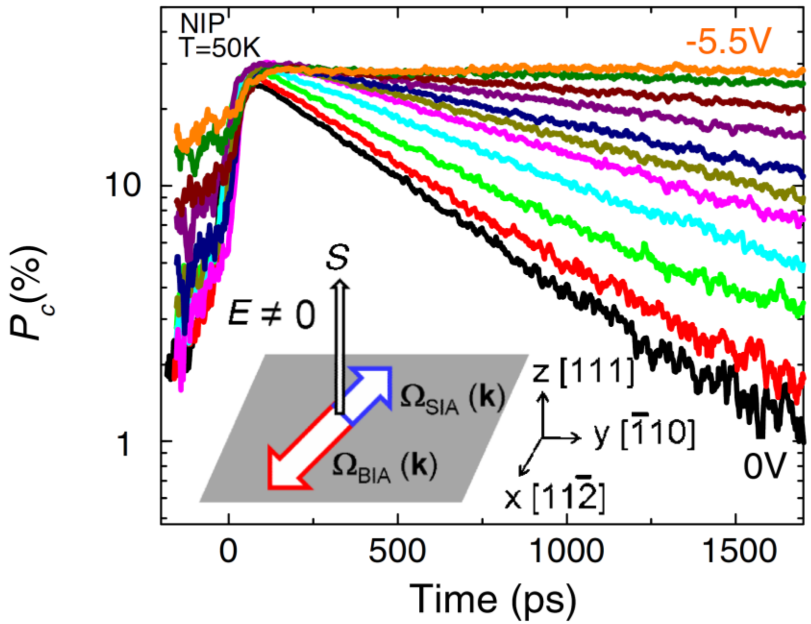
Experimental Results: τ_s^z

Electric field in the QW determined from measurements of the quantum confined Stark effect

What about τ_s^x and τ_s^y ??

<u>Sample II</u>

<u>N-I-P</u>



With stronger electric field, τ_s^z <u>increases</u> from 500 ps <u>to 30 ns</u>

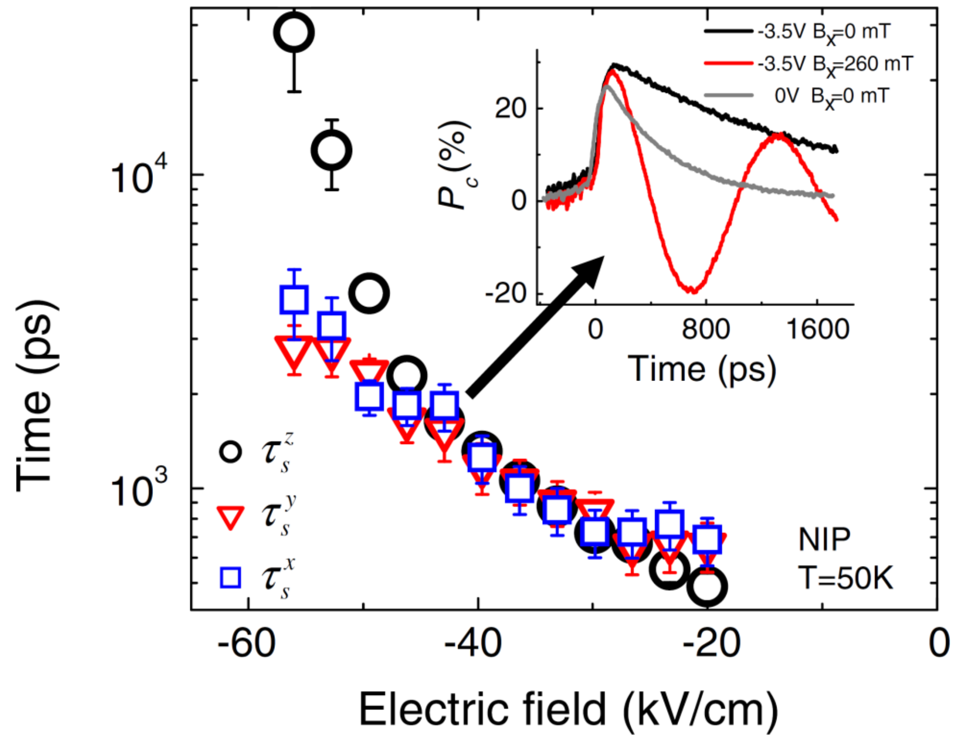
Experimental Results: τ_s^x and τ_s^y

To measure τ_s^y :

- Apply a magnetic field B_x along x
- σ+ pulse initializes the electron spins along the z axis
- Spins perform Larmor precessions within y-z plane, about B_x
- Measure combined spin relaxation rate Γ_{yz}
- Calculate τ_s^y via $\Gamma_{yz} = (1/\tau_s^y + 1/\tau_s^z)/2$

τ_s^x is obtained analogously, with a magnetic field B_y applied along y

Experimental Results: τ_s^x and τ_s^y



***V* = 0 V:**

τ_s^z = 490 ps

***V* = -3.5 V:**

τ_s^z = 1630 ps

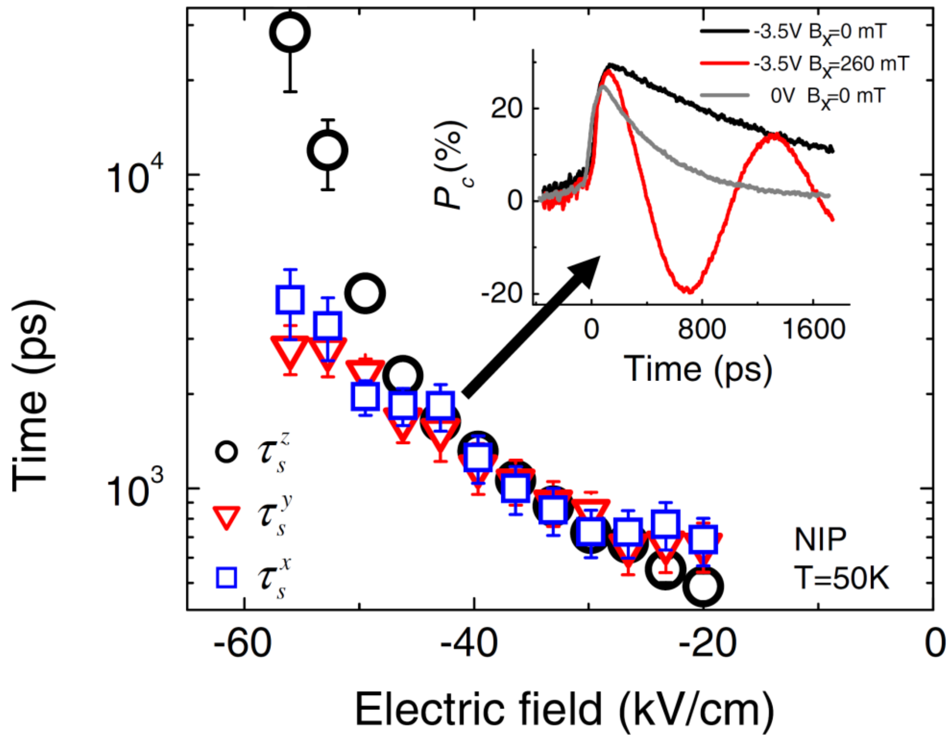
τ_s^x = 1830 ps

τ_s^y = 1530 ps

Relaxation times for x and y <u>also increase</u> with increasing electric field

At large applied fields, however, $\tau_s^x, \tau_s^y \ll \tau_s^z$

Experimental Results: τ_s^x and τ_s^y



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At large applied fields, however, $\tau_s^x, \tau_s^y \ll \tau_s^z$

Why??

Dresselhaus SOI

Dresselhaus SOI arises from bulk inversion asymmetry (BIA)

$$H_{\mathrm{BIA}}^{\mathrm{3D}}(\boldsymbol{k}) \propto (k_2^2 - k_3^2)k_1\sigma_1 + (k_3^2 - k_1^2)k_2\sigma_2 + (k_1^2 - k_2^2)k_3\sigma_3$$

1, 2, 3: main crystallographic axes

→ In contrast to Rashba SOI, the Dresselhaus term depends on the growth direction of the quantum well!

Effective QW Hamiltonian:
a) Rotate bulk term
b) Substitute $k_z^2 \to \langle k_z^2 \rangle$
$k_z, k_z^3 \to \langle k_z \rangle = \langle k_z^3 \rangle = 0$
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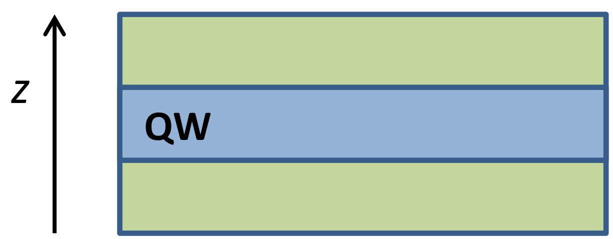
$$\boldsymbol{\Omega}_{\mathrm{BIA}}(\boldsymbol{k}_{\|}) = \frac{\gamma}{2\hbar}\langle k_z^2\rangle(0, 0, k_y) \quad \text{if } \mathbf{z} \parallel [110],$$

$$\boldsymbol{\Omega}_{\mathrm{BIA}}(\boldsymbol{k}_{\|}) = \frac{2\gamma}{\hbar\sqrt{3}}\langle k_z^2\rangle(k_y, -k_x, 0) \quad \text{if } \mathbf{z} \parallel [111]$$



SOI with Cubic Terms, [111]

$$\boldsymbol{\Omega}(\boldsymbol{k}_{\|}) = \boldsymbol{\Omega}_{\mathrm{SIA}}(\boldsymbol{k}_{\|}) + \boldsymbol{\Omega}_{\mathrm{BIA}}(\boldsymbol{k}_{\|})$$

$$\equiv \begin{cases} \Omega_x(\boldsymbol{k}_{\|}) = \frac{1}{\hbar}\left[\frac{\gamma}{\sqrt{3}}\left(2\langle k_z^2\rangle - \frac{k_{\|}^2}{2}\right) + aE\right]k_y \\ \Omega_y(\boldsymbol{k}_{\|}) = -\frac{1}{\hbar}\left[\frac{\gamma}{\sqrt{3}}\left(2\langle k_z^2\rangle - \frac{k_{\|}^2}{2}\right) + aE\right]k_x \\ \Omega_z(\boldsymbol{k}_{\|}) = \frac{1}{\hbar}\left(\frac{3k_x^2 k_y - k_y^3}{\sqrt{6}}\right). \end{cases}$$

For given $\boldsymbol{k}_{\|}$, only Ω_x and Ω_y can be fully removed by the Rashba term

$\longrightarrow$ Relaxation for spin along z can be suppressed more efficiently

Higher $\boldsymbol{k}$ states are populated with increasing temperature, leading to stronger fluctuations in $k_{\|}^2$.

At T = 150 K, an increase of τ_s^z by a factor of 5 could still be observed.

Summary

- In contrast to QWs grown along [001] or [110], electron spin relaxation via the Dyakonov-Perel mechanism can be suppressed simultaneously for all three spin orientations in [111] QWs
- This is due to complete compensation of the Rashba and Dresselhaus terms (in lowest order), and has now been evidenced experimentally
- For future applications, much stronger suppression even at room temperature is desired