# Hole Spin Relaxation in InAs & GaAs Quantum Dots:

## The Role of Dresselhaus Spin-Orbit Interaction

J. I. Climente, C. Segarra, J. Planelles

[1] Department of Physical and Analytical Chemistry, Universitat Jaume I, Castelló, Spain

E-mail: climente@uji.es

## Introduction

There are ongoing efforts to use the spin of holes in QDs for quantum information protocols. However, hole spin dynamics is not well understood yet: the spin-orbit admixture mechanism is still under debate. Different works *assume* different dominating mechanisms. Contradictory claims and observations follow:

HH-LH mixing dominant [1-2] ⟺ $k^3$ Dresselhaus SOI dominant [3] ⟺ k-linear Dresselhaus SOI dominant [4]

$T_1$ increases with lateral confinement [1] ⟺ $T_1$ decreases with lateral confinement [2]

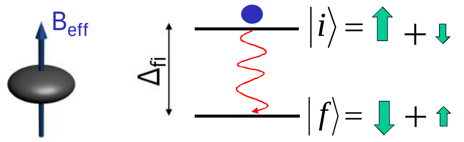
$T_1$ could exceed that of electrons in 2D QDs [3] ⟺ $T_1$ ~ 5-10 times shorter than that of electrons [5] (InAs QDs)

$T_1$ barely sensitive to energy splitting [6] (InAs QDs) ⟺ $T_1$ very sensitive to energy splitting [7] (CdSe rods)

We present a comprehensive study that clarifies the dominating SOI mechanisms and reconciles apparently contradictory predictions within a unified vision of the hole relaxation process [8]

## System and Model

Spin relaxation of holes in 3D spheroidal QDs




Transition mediated by acoustic phonons + SOI

$$\frac{1}{T_1} = \frac{2\pi}{\hbar} \sum_{\lambda \vec{q}} \left| \langle f | H_{h-ph}^{\lambda \vec{q}} | i \rangle \right|^2 \delta(\Delta_{fi} + E_q)$$

Hole-phonon coupling: piezoelectric + strain

Harmonic oscillator eigenstates (analytical matrix elements)

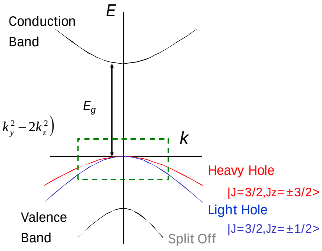
Hole states: $H_h = H_L + H_{BIA} + V_{QD}\, I + H_B$

$$\hat{H}_L = \begin{pmatrix} P+Q & -S & R & 0 \\ -S^* & P-Q & 0 & R \\ R^* & 0 & P-Q & S \\ 0 & R^* & S^* & P+Q \end{pmatrix} \begin{matrix} HH \Uparrow \\ LH \Uparrow + \Downarrow \\ LH \Downarrow + \Uparrow \\ HH \Downarrow \end{matrix}$$

$$P = \frac{1}{2m_0}\gamma_1 (k_x^2 + k_y^2 + k_z^2); \quad Q = \frac{1}{2m_0}\gamma_2 (k_x^2 + k_y^2 - 2k_z^2)$$

$$R = \frac{1}{2m_0}\left[-\sqrt{3}\gamma_2 (k_x^2 - k_y^2) + 2i\sqrt{3} k_x k_y\right]$$

$$S = \frac{1}{2m_0} 2\sqrt{3}\gamma_3 k_- k_z$$




$$H_{BIA} = \frac{2}{\sqrt{3}} C_k \left[k_x \{J_x, J_y^2 - J_z^2\} + cp\right] + b_{41}\left(\{k_x, k_y^2 - k_z^2\} J_x + cp\right) + b_{42}\left(\{k_x, k_y^2 - k_z^2\} J_x^3 + cp\right) + b_{51}\left(\{k_x, k_y^2 + k_z^2\}\{J_x, J_y^3 - J_z^3\} + cp\right) + b_{52}\left(k_x^3 \{J_x, J_y^3 - J_z^3\} + cp\right)$$

$$H_{b41} = \begin{pmatrix} \frac{3}{2}P_{41} & \frac{\sqrt{3}}{2}L_{41} & 0 & 0 \\ \frac{\sqrt{3}}{2}L_{41}^* & \frac{1}{2}P_{41} & L_{41} & 0 \\ 0 & L_{41}^* & -\frac{1}{2}P_{41} & \frac{\sqrt{3}}{2}L_{41} \\ 0 & 0 & \frac{\sqrt{3}}{2}L_{41}^* & -\frac{3}{2}P_{41} \end{pmatrix}$$

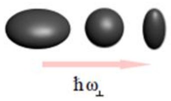
$$P_{41} = (k_y^2 - k_z^2) k_z$$

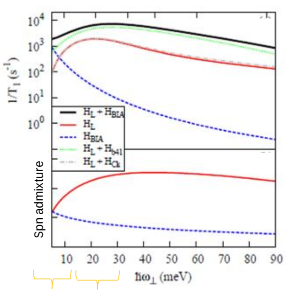
$$L_{41} = i k_- k_x k_y - k_+ k_z^2$$

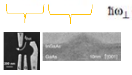
$$H_{Ck} = \begin{pmatrix} 0 & -\frac{k_-}{2} & k_z & -\frac{\sqrt{3}k_-}{2} \\ -\frac{k_+}{2} & 0 & \frac{\sqrt{3}k_+}{2} & -k_z \\ k_z & \frac{\sqrt{3}k_-}{2} & 0 & -\frac{k_-}{2} \\ -\frac{\sqrt{3}k_+}{2} & -k_z & -\frac{k_+}{2} & 0 \end{pmatrix}$$

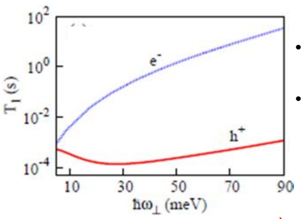
## Results

### Radial confinement






**Mechanism**

- $1/T_1$ reflects degree of spin admixture
- $H_{BIA}$ dominates for weak confinement
- $H_{Ck}$ negligible
- $H_L$ + $H_{b41}$ required for realistic estimates

**General features**

- $T_1$ drastically different from electrons
- Non-monotonic trend

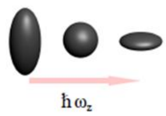
$$\Psi_h = \Psi_{HH}^{\Uparrow} + \ldots + \frac{\langle \Psi_{HH}^{\Downarrow} | H' | \Psi_{LH}^{\Downarrow} \rangle \langle \Psi_{LH}^{\Downarrow} | H' | \Psi_{HH}^{\Uparrow} \rangle}{(E_{HH}^{\Uparrow} - E_{HH}^{\Downarrow})(E_{HH}^{\Uparrow} - E_{LH}^{\Downarrow})} \Psi_{HH}^{\Downarrow}$$

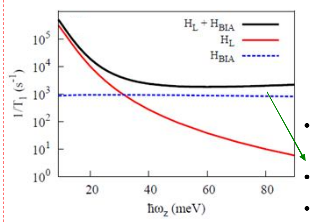
Stronger SOI

LH closer to HH

Reconciles [1] and [2]

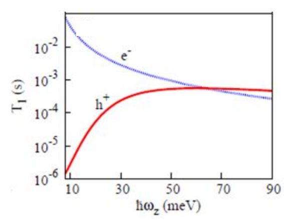
### Vertical confinement




**Mechanism**

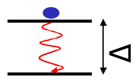
- $H_L$ dominates for weak confinement
- Saturation limit set by $H_{BIA}$
- $H_L$ + $H_{b41}$ required for realistic estimates

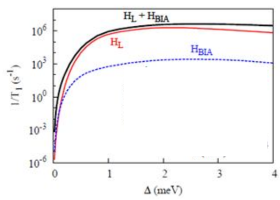



**General features**

- $T_1$ drastically different from electrons
- In gated QDs with narrow well $T_1^h > T_1^e$

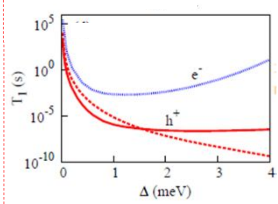
### Spin splitting energy




**Mechanism**

- $H_{BIA}$ dominates for very narrow splittings due intrinsic to zero-field splitting




**General features**

- Prolate QDs: sensitive to Δ (consistent with [6])
- Oblate QDs: sensitive to small Δ values

*Two-phonon processes relevant in [6]* ?

## Conclusion

In quasi-2D QDs Dresselhaus SOI is comparable (self-assembled QDs) or even larger (gated QDs) than HH-LH mixing. The simultaneous action of both mechanisms enhances spin relaxation rates by orders of magnitude.

## References

**[1]** Woods et al, Phys. Rev. B 69, 125330 (2004); **[2]** Lü et al. Phys. Rev. B 71, 075308 (2005); **[3]** Bulaev et al. Phys. Rev. Lett. 95, 076805 (2005); **[4]** Tsitsishvili et al. Phys. Rev. B 72, 155333 (2005); **[5]** Heiss et al. Phys. Rev. B 76, 241306R (2007); **[6]** Kurtze et al. Phys. Rev. B 85, 195303 (2012); **[7]** He et al. Phys. Rev. Lett. 105, 046601 (2010);
**[8] Climente et al. arXiv:1301.4381.**