Columnar quantum dots (QD) in polarization insensitive SOA and non-radiative Auger processes in QD: a theoretical study

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Outline

I- k.p axial approximation

II- Columnar quantum dots (QD) in polarization insensitive semiconductor optical amplifiers (SOA)

III- Non radiative Auger process in QD

IV- Conclusion

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Quantum dot with axial symmetry

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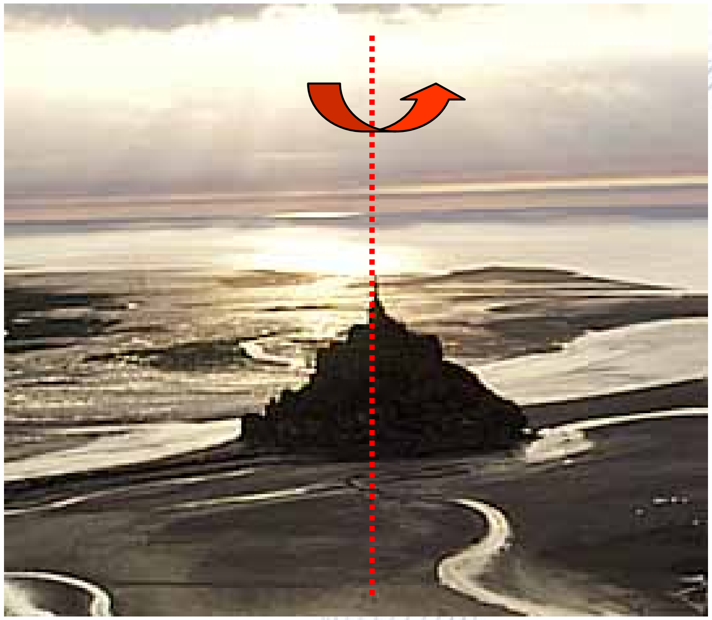
Geometry of quantum dot : $C_{\infty v}$ symmetry



A new description in cylindrical coordinates : **r, φ, z**

Some references for k.p axial approximation :

[1] P. Enders and M. Woerner, SST (1996) : **k-dependent 4x4 block-diag. of 8x8 Ham. (Bulk)**

[2] C. Y. P. Chao and S. L. Chuang, PRB (1992) : **k-ind. block-diag. of 6x6 Ham. (QW)**

[3] Y. M. Mu and S. S. Pei, JAP (2004) : **k-ind. block-diag. of 8x8 Ham. (QW)**

[4] K. J. Vahala and P. C. Sercel, PRL, PRB (1990) : **k-ind. block-diag. of 8x8 Ham. (Qwire and Spherical QD)**

[5] M. Tadic, F.M. Peeters and K. J. Janssens, JAP, PRB (2002, 2004) **k-ind. block-diag. of 6x6 Ham. (QD)**

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Axial approximation for mechanical properties

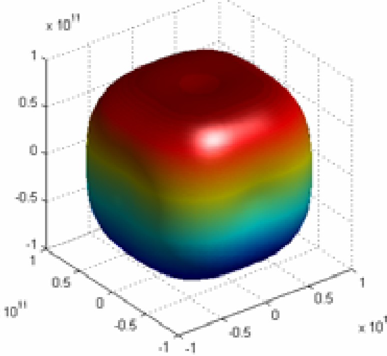
Acoustic phonon band “warping” in cubic materials

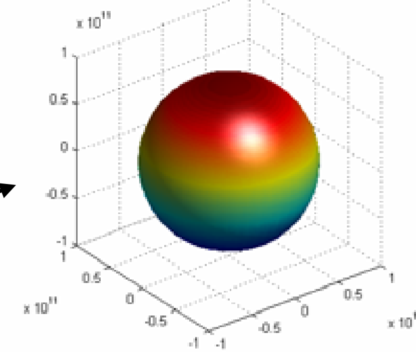
A test : → sound velocities in InAs

Surfaces : angular dependence of the longitudinal velocity

Even et al, APL (2007) *P04-P12*

Cubic material



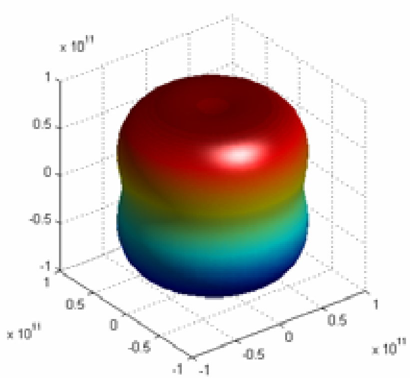


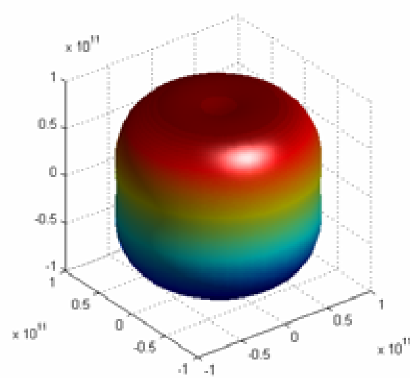
“3D isotropic“ approx.

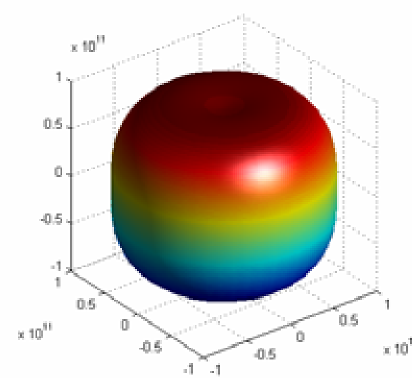
$d = 0$

$d = 0.5$

$d = 1$







“Transverse isotropic“ approx.

$$\overline{C} = \frac{C_{11} - C_{12}}{2} + \left(C_{44} - \frac{C_{11} - C_{12}}{2} \right) d$$

Axial approximation for mechanical properties

Description in cylindrical coordinates : r, ϕ, z $\longrightarrow \varepsilon_{rr}, \varepsilon_{\varphi\varphi}, \varepsilon_{zz}, \varepsilon_{rz}$

"Transverse isotropic" approx. for cubic materials

$$\begin{pmatrix} C'_{11} & C'_{12} & C_{12} & 0 & 0 & 0 \\ C'_{12} & C'_{11} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{12} & C_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & \overline{C} \end{pmatrix}$$

$$C'_{11} = \frac{C_{11} + C_{12}}{2} + \overline{C}$$

$$C'_{12} = \frac{C_{11} + C_{12}}{2} - \overline{C}$$

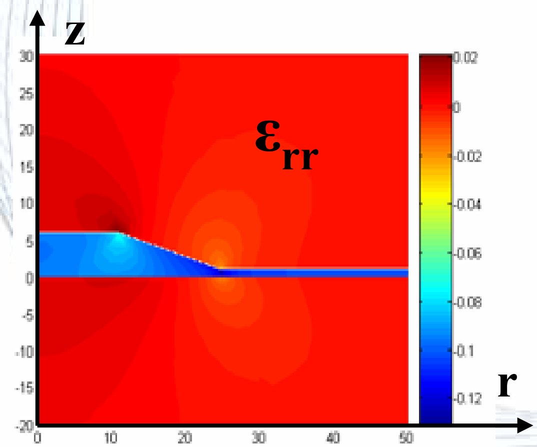
4 parameters

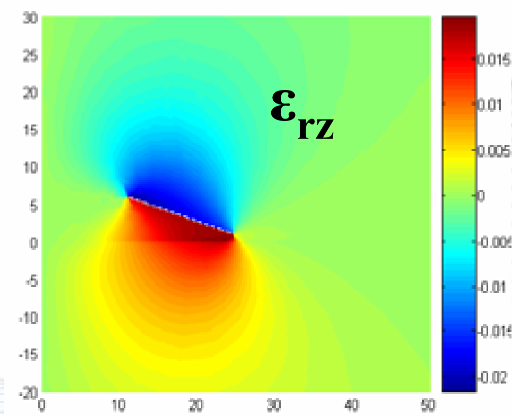
Back to cartesian coordinates $\longrightarrow$

$$\varepsilon_{xx} = \cos^2(\varphi)\varepsilon_{rr} + \sin^2(\varphi)\varepsilon_{\varphi\varphi} \qquad \varepsilon_{xz} = \cos(\varphi)\varepsilon_{rz} \qquad \varepsilon_{xy} = \frac{\sin(2\varphi)}{2}(\varepsilon_{rr} - \varepsilon_{\varphi\varphi})$$

$$\varepsilon_{yy} = \sin^2(\varphi)\varepsilon_{rr} + \cos^2(\varphi)\varepsilon_{\varphi\varphi} \qquad \varepsilon_{yz} = \sin(\varphi)\varepsilon_{rz}$$

Example : InAs/GaP QD





Axial approximation for the 8-band k.p strained Hamiltonian

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Unstrained part :

$$R = -\sqrt{3}\frac{\hbar^2}{2m_0}\left[\gamma_2\left(k_x^2 - k_y^2\right) - 2i\gamma_3 k_x k_y\right] \approx -\sqrt{3}\frac{\hbar^2}{2m_0}\bar{\gamma}k_-^2$$

Strained part :
(new proposition)

$$\boldsymbol{R}_\varepsilon = \frac{\boldsymbol{b}\sqrt{3}}{2}\left(\boldsymbol{\varepsilon}_{rr} - \boldsymbol{\varepsilon}_{\varphi\varphi}\right)\cos(2\boldsymbol{\varphi}) - \boldsymbol{i}\frac{\boldsymbol{d}}{2}\left(\boldsymbol{\varepsilon}_{rr} - \boldsymbol{\varepsilon}_{\varphi\varphi}\right)\sin(2\boldsymbol{\varphi}) \approx \frac{\bar{\boldsymbol{b}}\sqrt{3}}{2}\left(\boldsymbol{\varepsilon}_{rr} - \boldsymbol{\varepsilon}_{\varphi\varphi}\right)\boldsymbol{e}^{-i2\varphi}$$

$$\frac{\bar{\boldsymbol{b}}\sqrt{3}}{2} = \frac{1}{2}\left(\frac{\boldsymbol{b}\sqrt{3}}{2} + \frac{\boldsymbol{d}}{2}\right)$$

InAs	$\frac{b\sqrt{3}}{2} = -1.58eV$	$\frac{d}{2} = -1.80eV$
GaAs	$\frac{b\sqrt{3}}{2} = -1.56eV$	$\frac{d}{2} = -2.25eV$
InP	$\frac{b\sqrt{3}}{2} = -1.73eV$	$\frac{d}{2} = -2.50eV$

Even et al, PRB (2008)

$$\boldsymbol{A}_\varepsilon = \boldsymbol{a}_c\left(\boldsymbol{\varepsilon}_{rr} + \boldsymbol{\varepsilon}_{\varphi\varphi} + \boldsymbol{\varepsilon}_{zz}\right)$$

$$\boldsymbol{P}_\varepsilon = \boldsymbol{a}_v\left(\boldsymbol{\varepsilon}_{rr} + \boldsymbol{\varepsilon}_{\varphi\varphi} + \boldsymbol{\varepsilon}_{zz}\right)$$

Hydrostatic strain

$$\boldsymbol{Q}_\varepsilon = \boldsymbol{b}\left(\boldsymbol{\varepsilon}_{zz} - \frac{\boldsymbol{\varepsilon}_{rr} + \boldsymbol{\varepsilon}_{\varphi\varphi}}{2}\right)$$

Biaxial strain

$$\boldsymbol{R}_\varepsilon = \frac{\bar{\boldsymbol{b}}\sqrt{3}}{2}\left(\boldsymbol{\varepsilon}_{rr} - \boldsymbol{\varepsilon}_{\varphi\varphi}\right)\boldsymbol{e}^{-i2\varphi}$$

$$S_\varepsilon = -d\varepsilon_{rz}e^{-i\varphi}$$

Shear strain

Axial approximation for the 8-band k.p strained Hamiltonian

Block diagonalization of the Hamiltonian for each Fz value :

A good quantum number : total angular momentum $F_z = J_z + L_z$

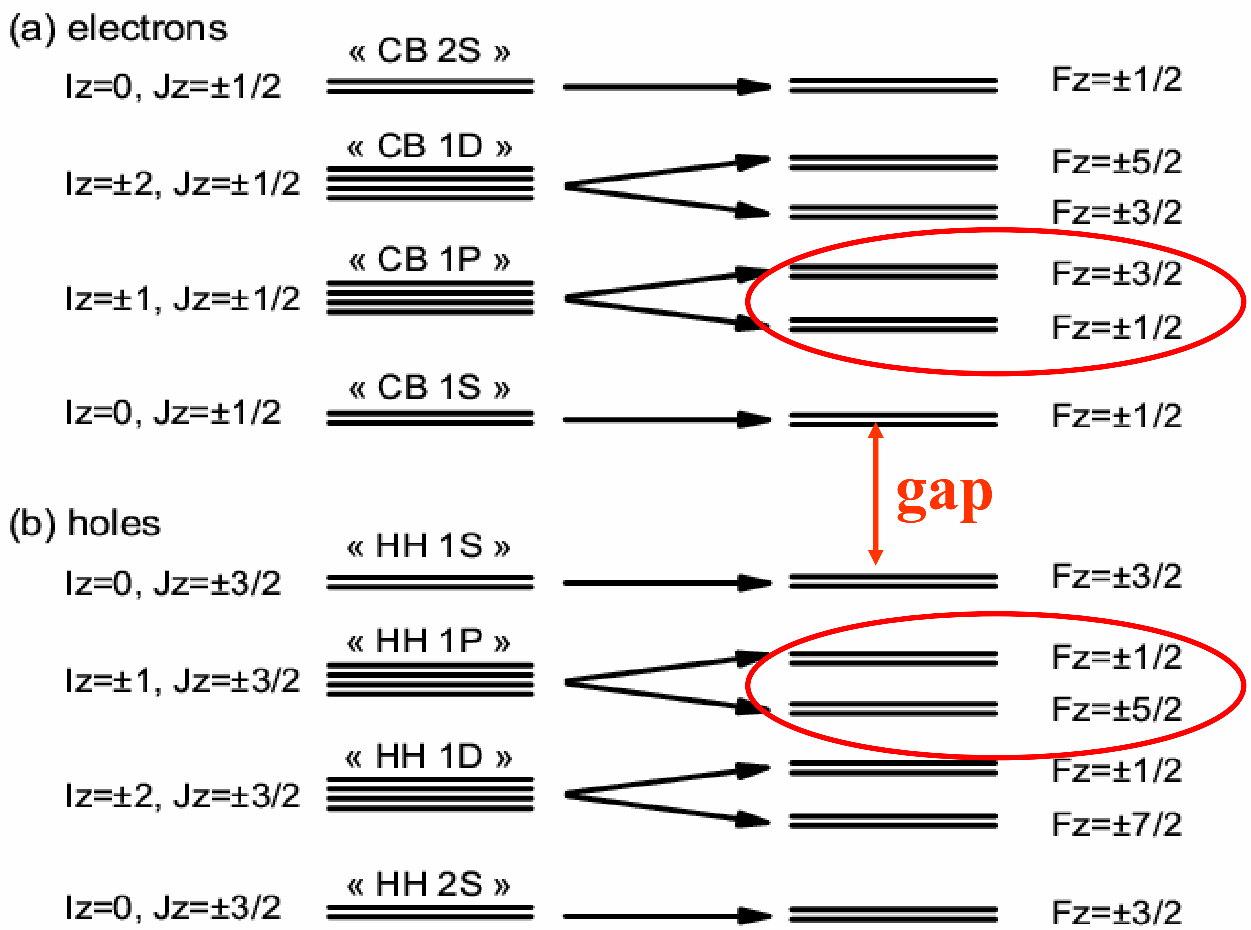
Development of the wavefunction : $\left| J, J_z \right\rangle \left| L_z = F_z - J_z \right\rangle$

Basis of 8 Bloch functions u_i (i=1…8) 8 enveloppe functions of (r,z)

J_Z	F_z	-5/2	-3/2	-1/2	1/2	3/2	5/2
1/2	L_{z1} (CB)	-2	-1	0	+1	+2	+3
-1/2	L_{z2} (CB)	-3	-2	-1	0	+1	+2
-1/2	L_{z3}	-3	-2	-1	0	+1	+2
-3/2	L_{z4} (HH)	-4	-3	-2	-1	0	+1
3/2	L_{z5} (HH)	-1	0	+1	+2	+3	+4
1/2	L_{z6}	-2	-1	0	+1	+2	+3
1/2	L_{z7}	-2	-1	0	+1	+2	+3
-1/2	L_{z8}	-3	-2	-1	0	+1	+2

Axial approximation for the 8-band k.p strained Hamiltonian

Excited "p"and "d" states splitting predicted from symmetry analysis



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Columnar QD for polarization insensitive SOA

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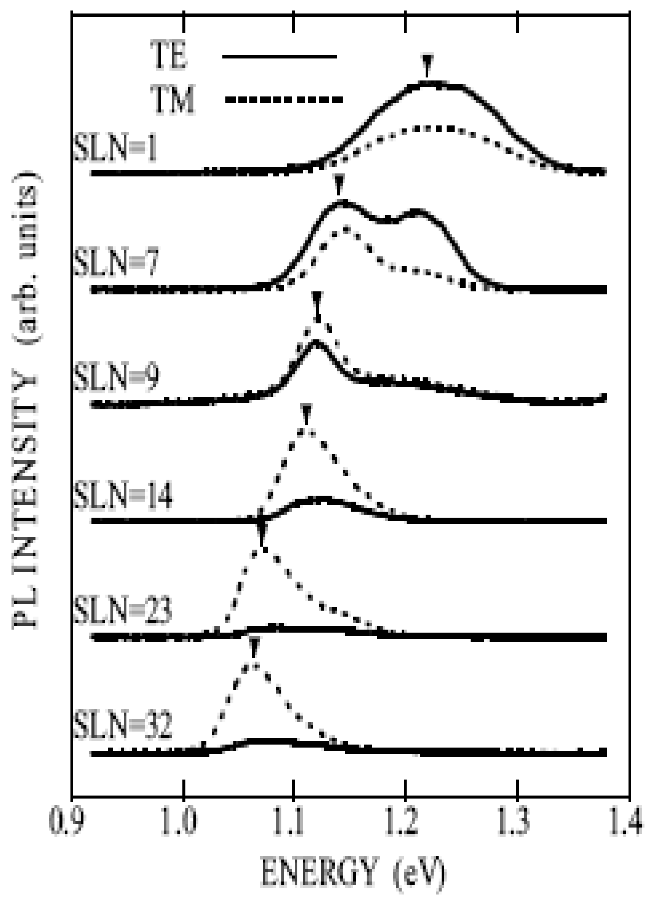
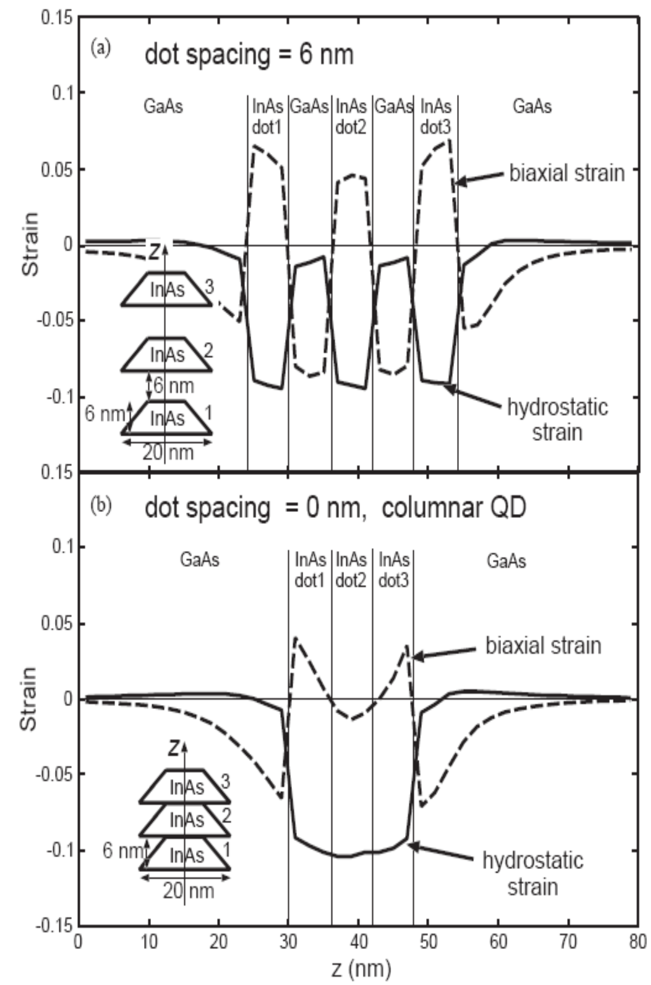
InAs/GaAs



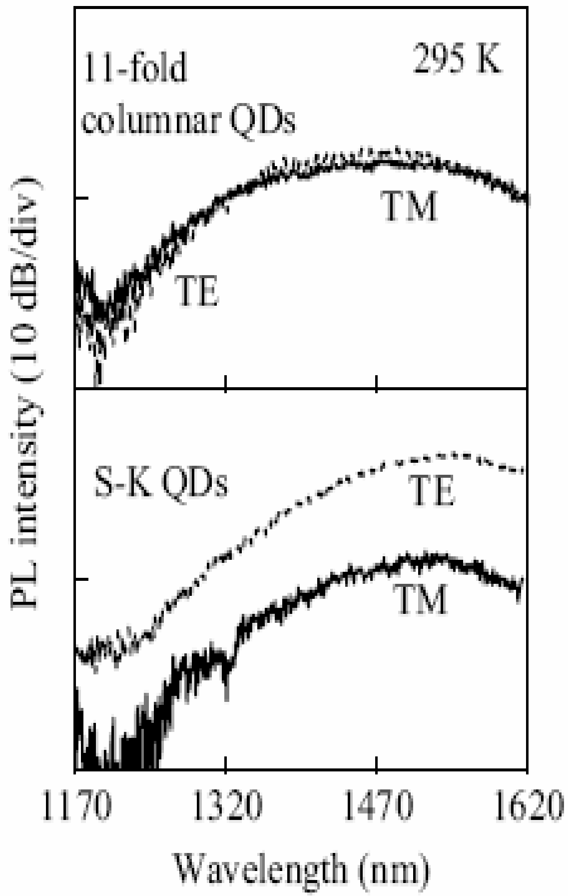
Kita, Phys. Stat. Sol. (2003)



Saito, Physica E (2005)

Columnar QD for polarization insensitive SOA

InAs/InP



Kawagushi, Phys. Stat. Sol. (2006)

Transitions between 2 states F_{z1}/F_{z2}

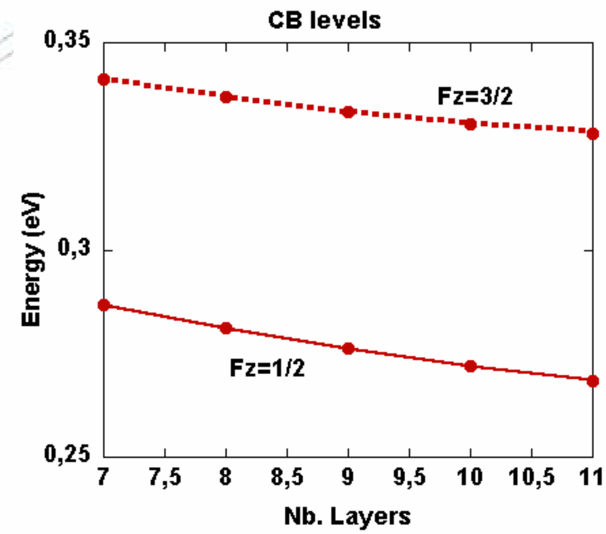
TE absorption :

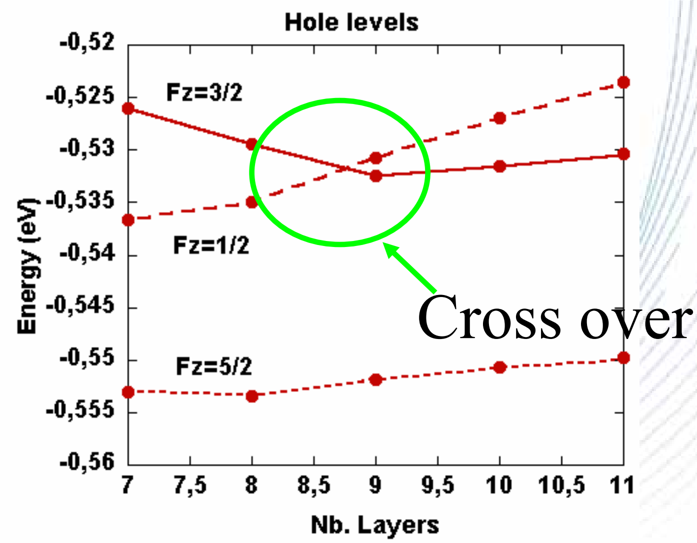
$$\Delta F = |F_{z1} - F_{z2}| = \pm 1$$

TM absorption :

$$\Delta F = |F_{z1} - F_{z2}| = 0$$

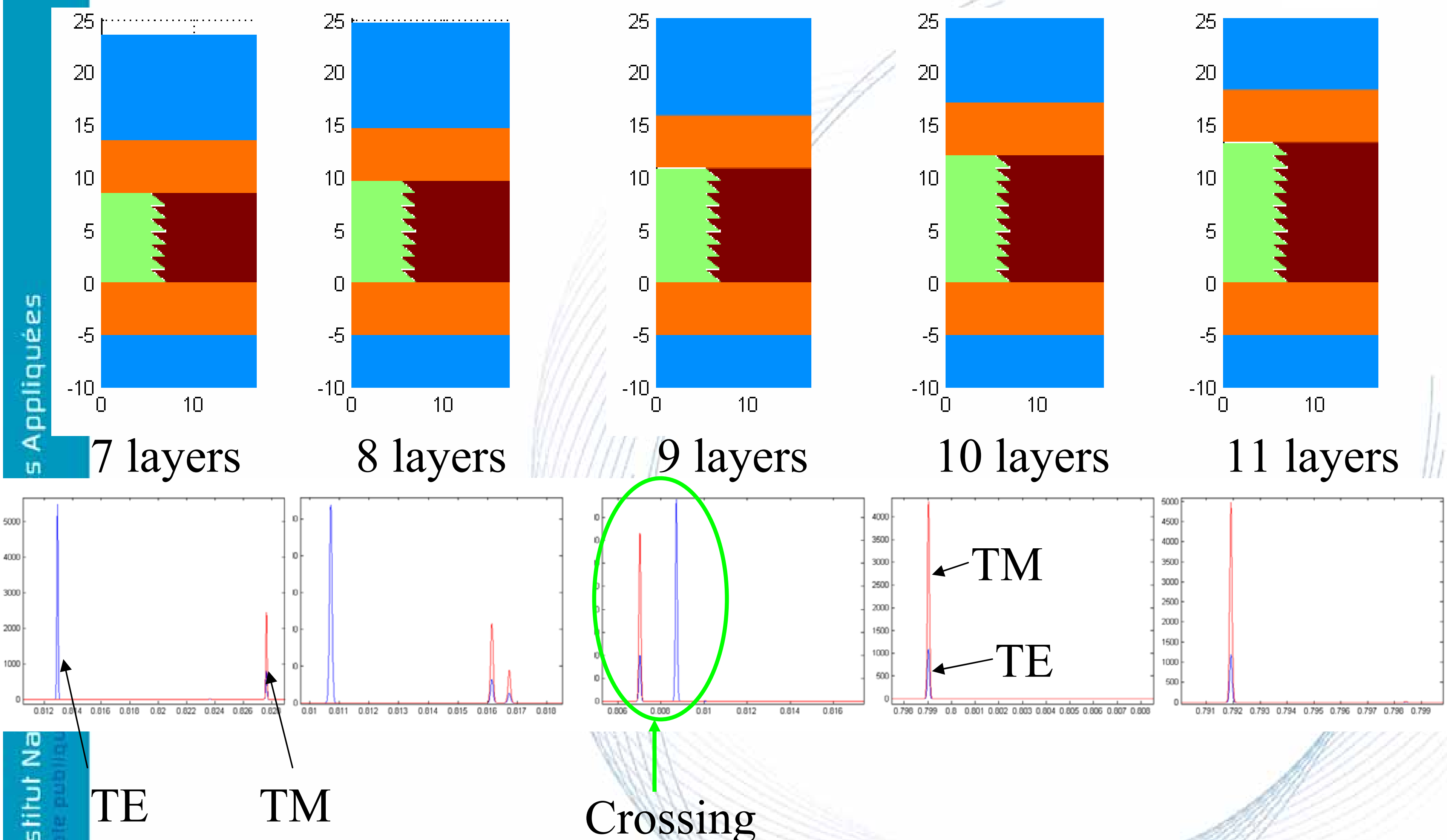
In 1 QD :
Electron GS : $F_Z = \pm 1/2$,
Hole GS : $F_Z = \pm 3/2$
TE transitions





This model

Columnar QD for polarization insensitive SOA



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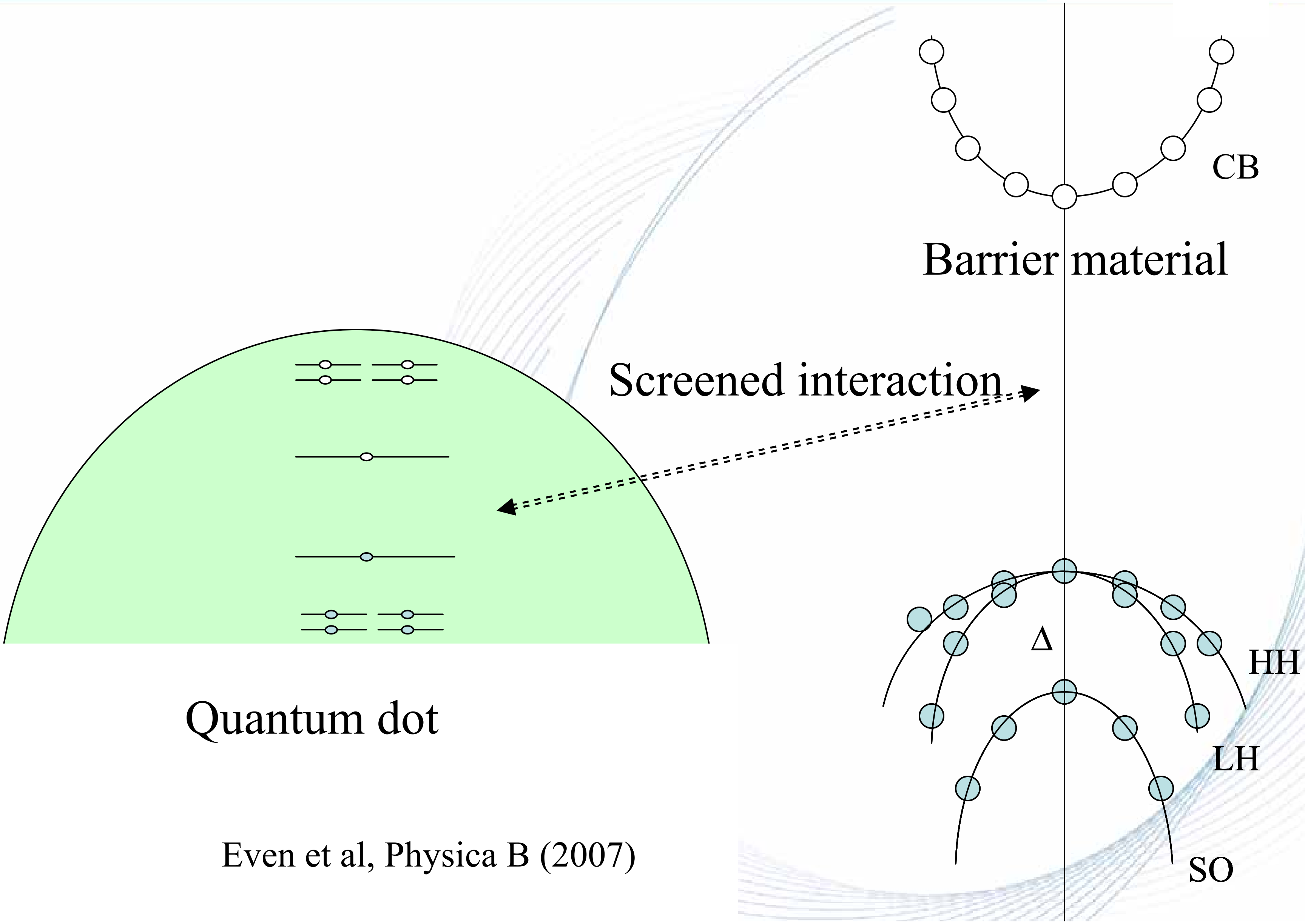
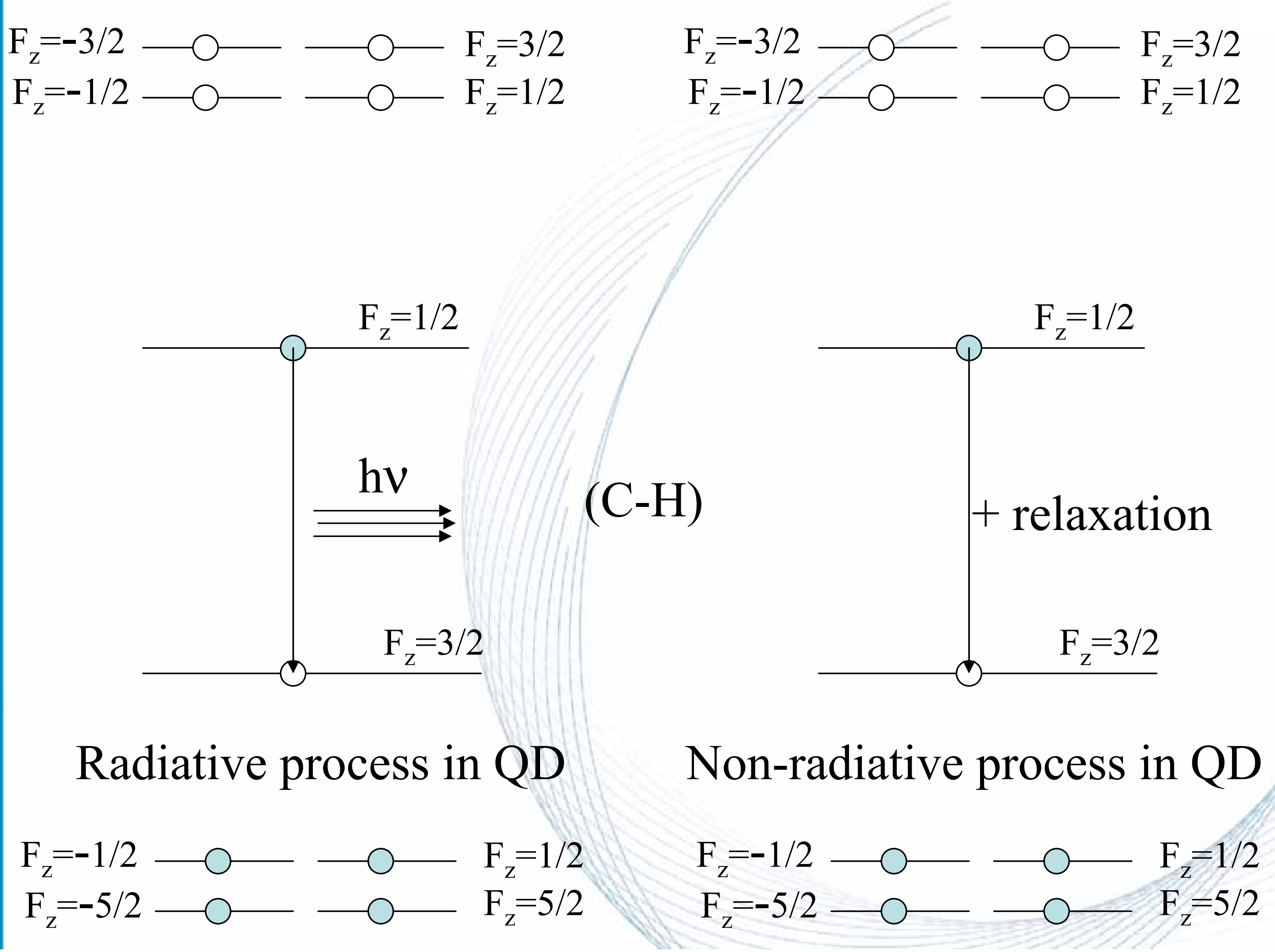
Auger processes in narrow gap QD

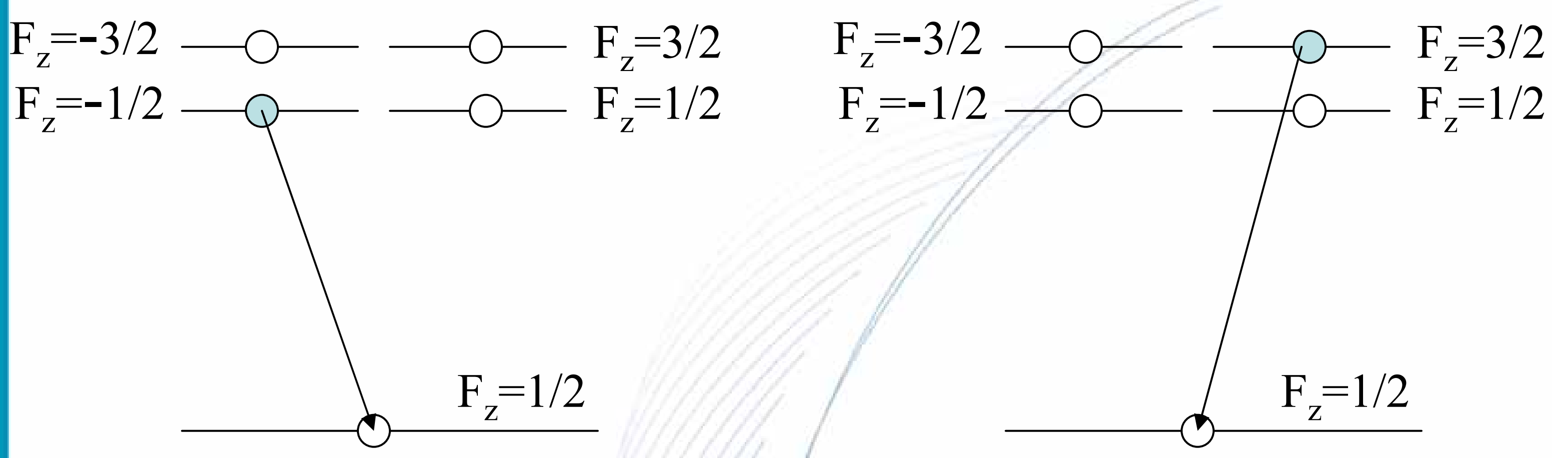


Even et al, Physica B (2007)

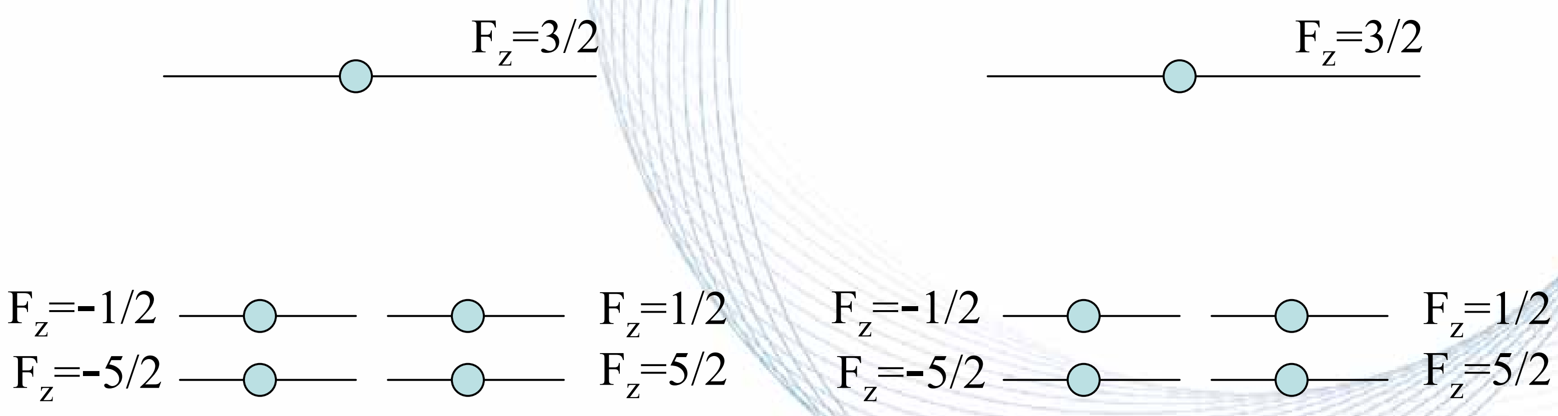
Auger processes in narrow gap QD



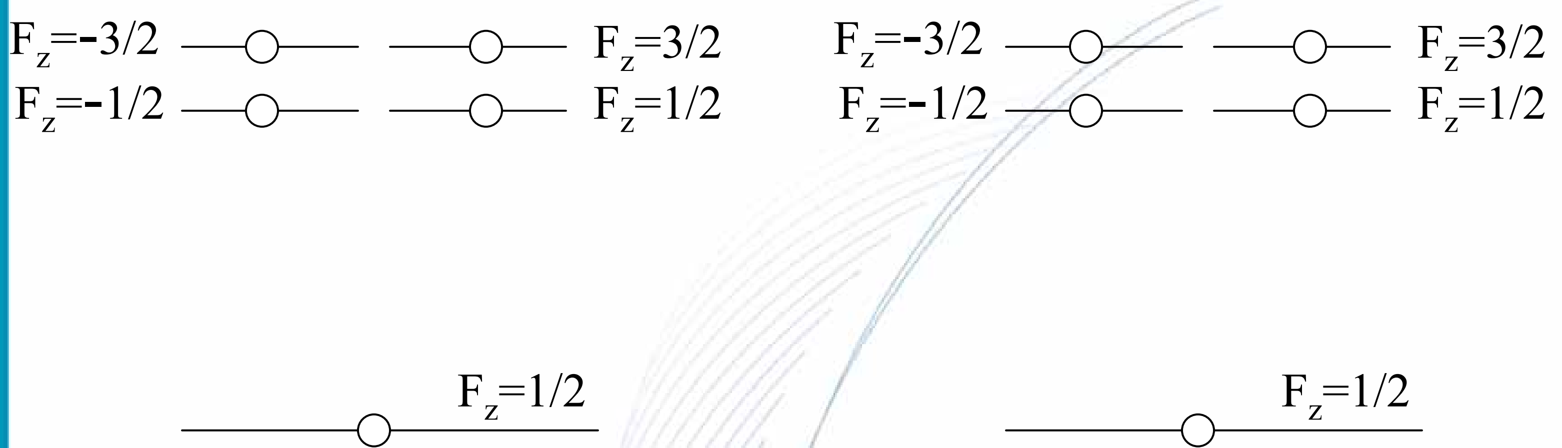
Auger processes in narrow gap QD



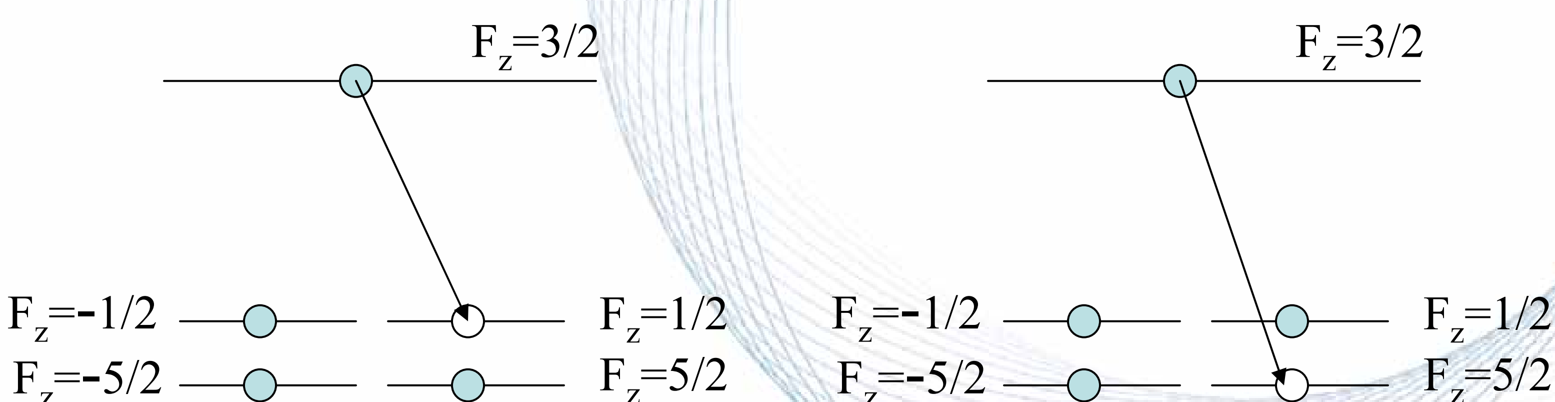
CB relaxation in QD (C-C)



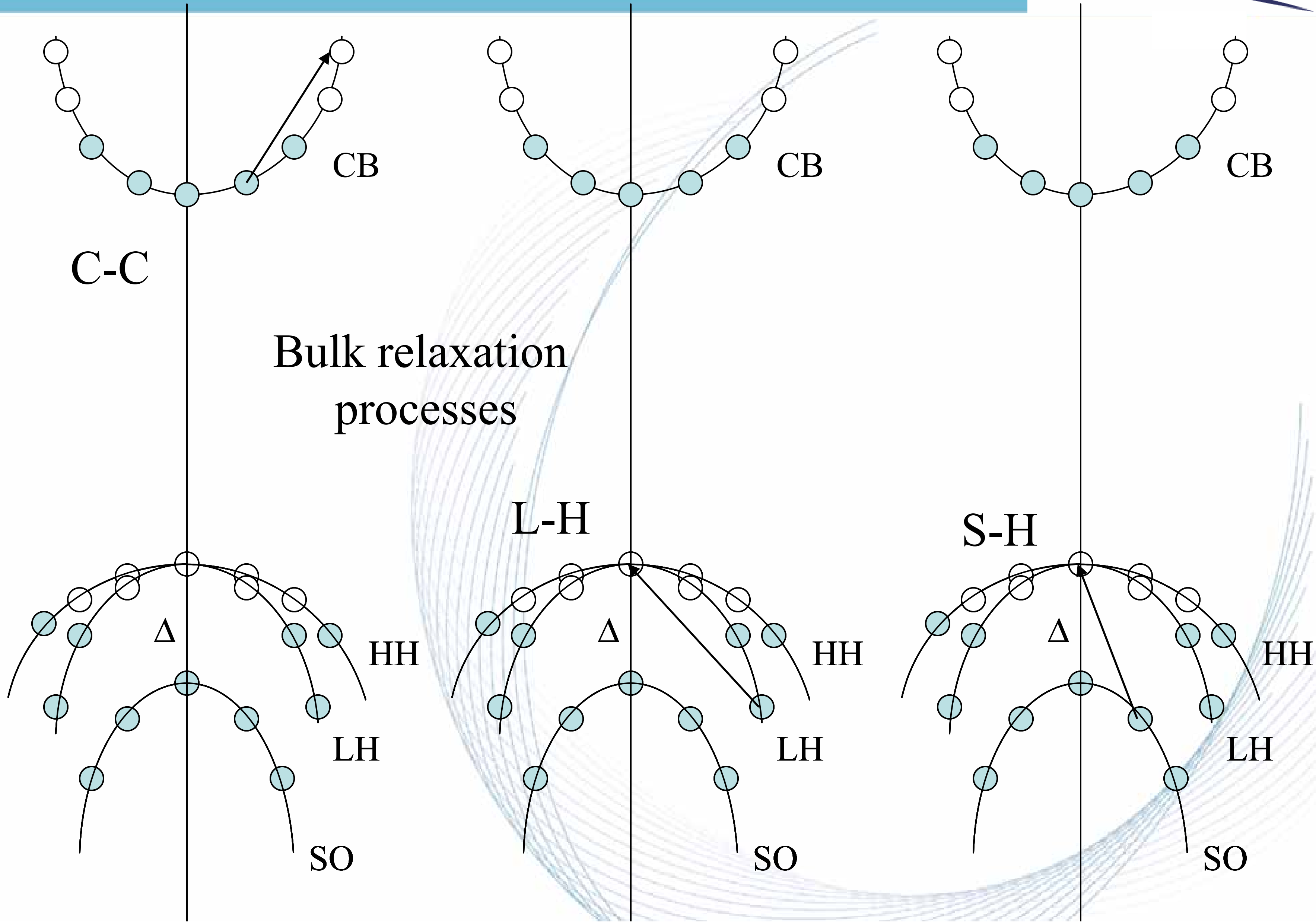
Auger processes in narrow gap QD



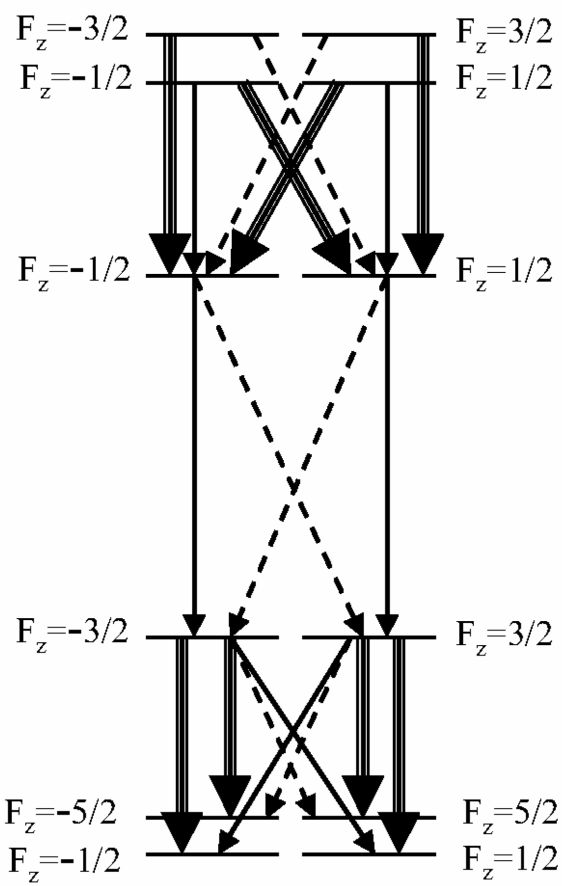
Hole relaxation in QD (H-H)



Auger processes in narrow gap QD



Auger processes in narrow gap QD



Example : InAs/Q1.18/InP truncated cone QD

E_{CH}=0.77eV (gap) E_{CC}=23meV E_{HH}=16meV
$N_{Bulk}=10^{18}cm^{-3}$

Non-radiative processes :

τ_{CHCC}= 0.2µs τ_{CHLH}=1.1ms τ_{CHSH}=14ns

CB relaxation in QD :

τ_{CCCC}=0.74ps τ_{CCLH}=24ps $\tau_{CCSH}=\infty$

Hole relaxation in QD :

τ_{HHCC}=1.0ps τ_{HHLH}=22ps $\tau_{HHSH}=\infty$

Conclusion : further studies…

- New axially symmetric strained nanostructures
- Auger effects (gap influence, comparison WL/bulk, barrier materials, hydrostatic pressure…)
- Beyond the 8-band k.p approximation