Excitons in self-assembled type- II quantum dots and coupled dots

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Condensed Matter
Theory

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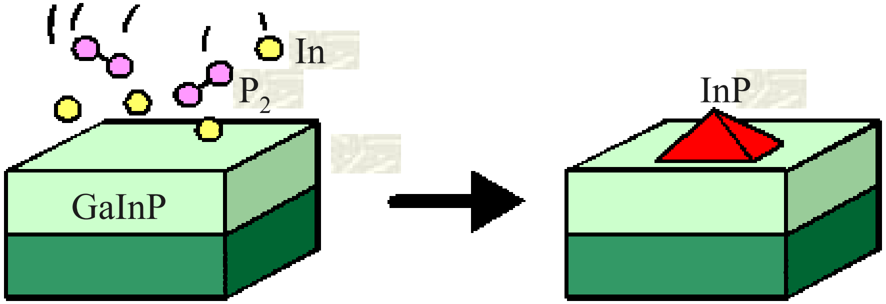
Self-assembled quantum dots

Necessary ingredients:

2 semiconductor materials with a substantially different lattice parameter, e.g.

InP : a ~ 5.869 Å   and GaInP : a ~ 5.653 Å   (mismatch ~ 3.8%)

MBE growth



Result

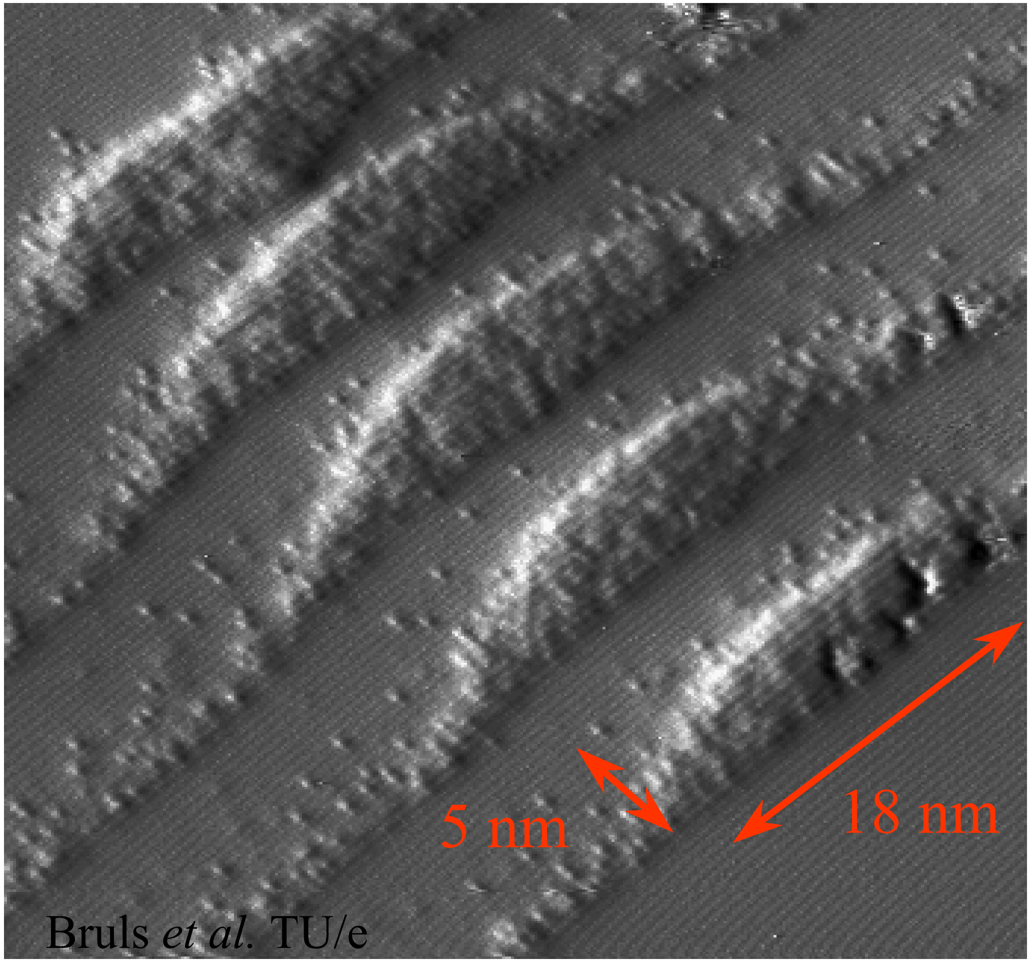
lattice mismatch □ strain fields □ formation of islands

□

self-assembled quantum dots

Stack of InAs Quantum Dots

self assembly &
self organization

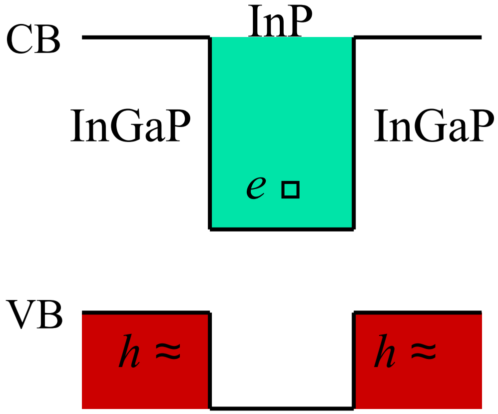


Bruls *et al.* TU/e

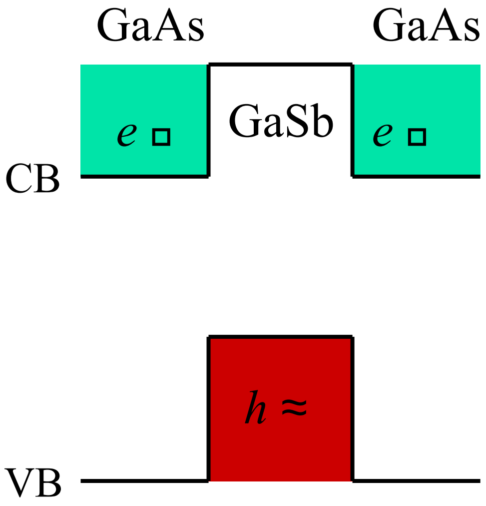
Appl. Phys. Lett. **81**, 1708 (2002)

Different type-II systems

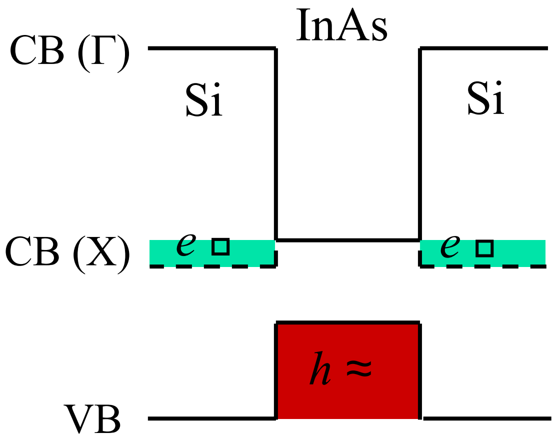
electron in the dot, hole outside
e.g. InP/GaInP dots



hole in the dot, electron outside
e.g. GaSb/GaAs dots



InAs/Si dots



Theoretical approach

- **Strain:** approach of J.R. Downes *et al.,* JAP **81**, 6700 (1997); J.H. Davies, JAP **84**, 1358 (1998):

$$\varepsilon_{ij}(\vec{r}) = \varepsilon_o \delta_{ij} - \frac{\varepsilon_o}{4\pi}\frac{1+\nu}{1-\nu}\oiint_{S'} dS'_j \frac{r_i - r_i'}{|\vec{r} - \vec{r}\,'|^3}$$

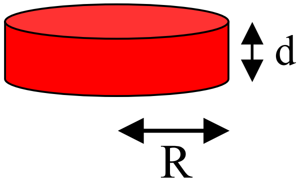
- **Band structure:** effective ‘anisotropic’ mass (following the ideas of L.R. Wilson *et al.*, Phys. Rev. B **57**, R2073 (1998) – which was successfully applied to InAs/GaAs SAQD’s).
- **Exciton energy:** Hartree-Fock approximation

→ advantages: much faster numerical program + magnetic field can easily be included

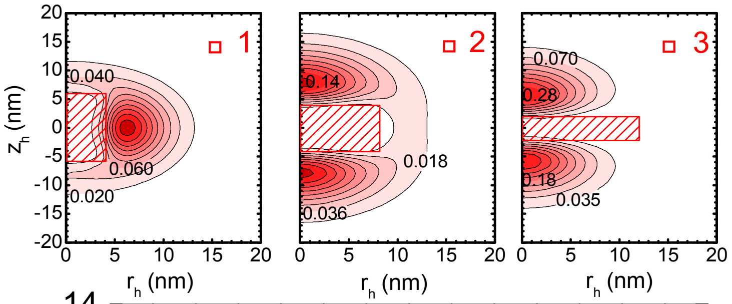
No strain

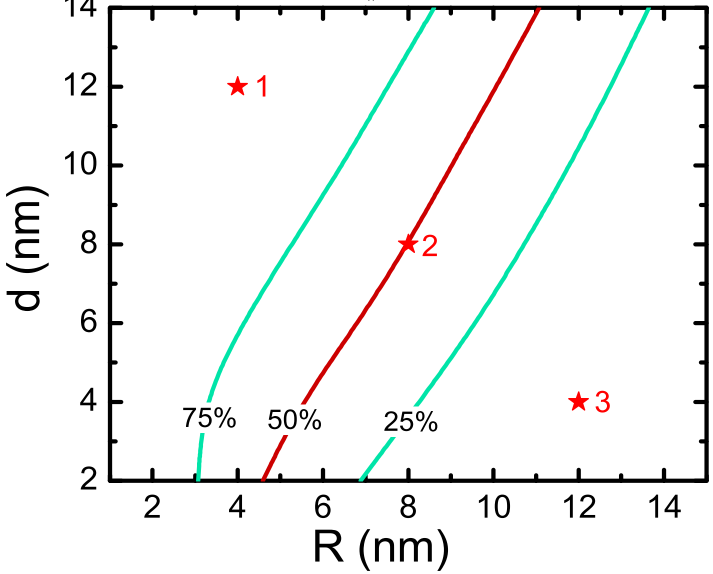
Only Coulomb interaction

Single dots



the hole can sit: - at the radial boundary of the dot
- above/below the disk





❖ Study of the influence of the disk parameters *d* and *R* (at $B = 0T$)

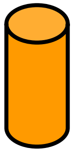
$$P_{side} = 2\pi \int_{-\infty}^{\infty} dz_h \int_{R}^{\infty} r_h \left|\psi_h\left(r_h, z_h\right)\right|^2 dr_h$$

Distinguish between 2 regimes:

❖ disk-like regime: $d << 2R$

(□ 3)

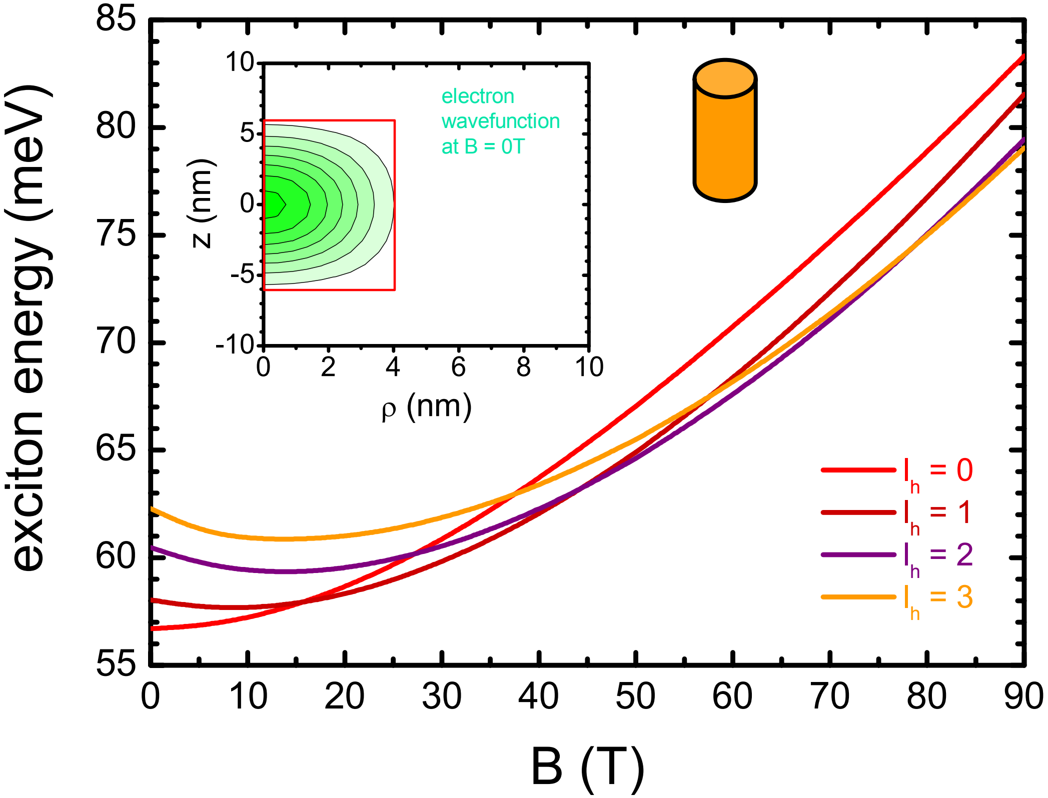
❖ pillar-like regime: $d >> 2R$

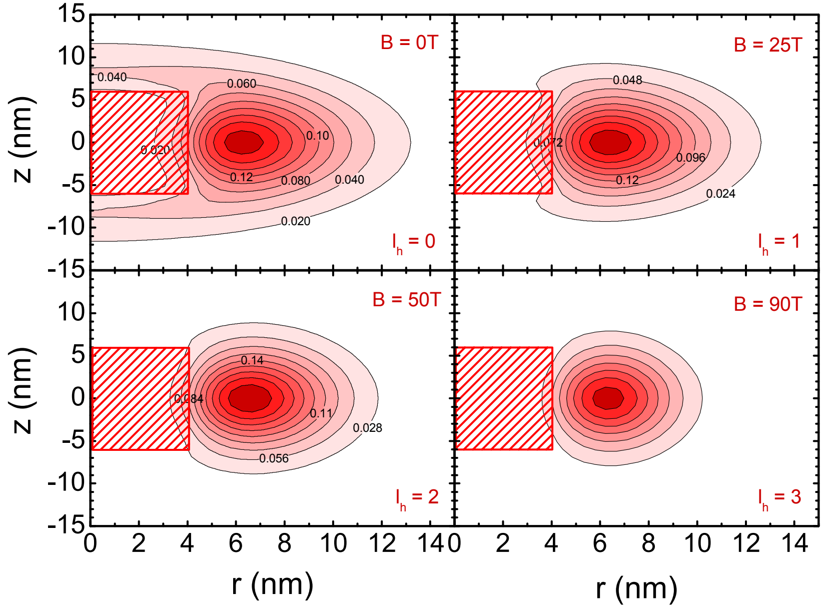


(□ 1)

Pillar-like system

d =12 nm, R = 4nm



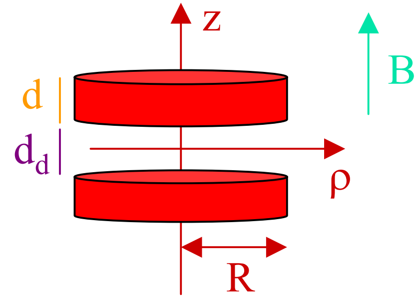


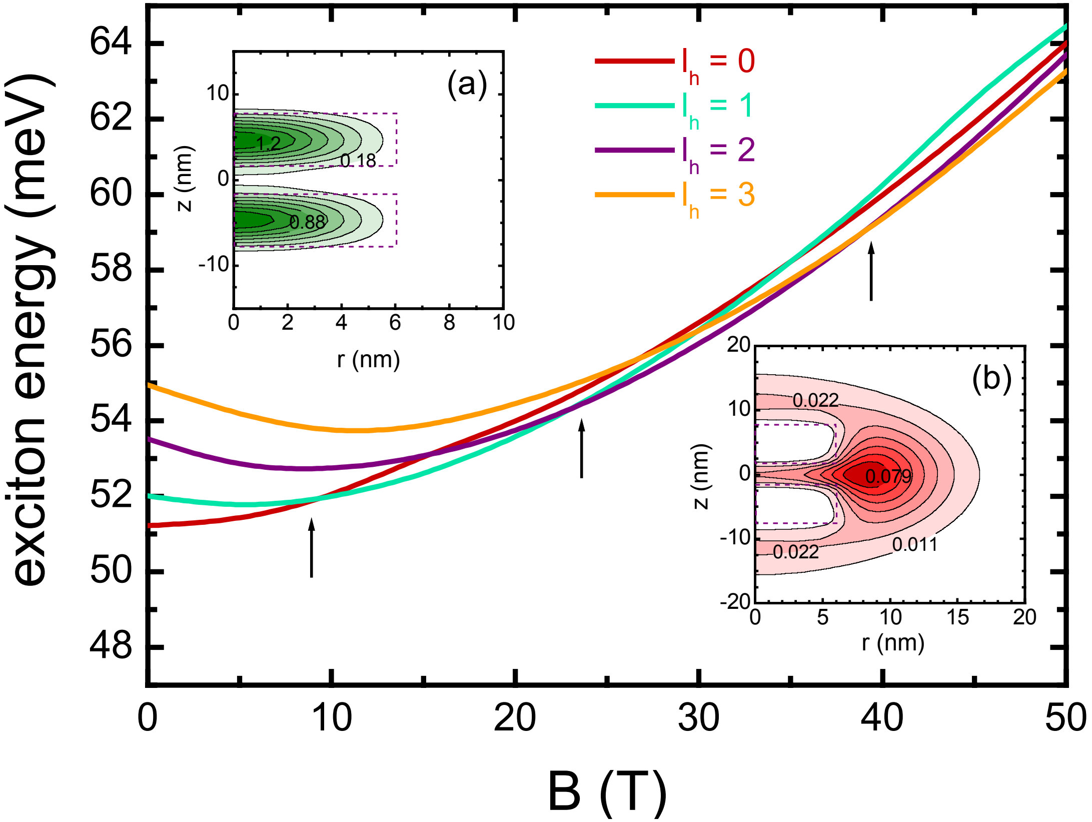
- ❖ the hole is sitting at the radial boundary of the quantum disk
- ❖ appearance of *angular momentum transitions*

Vertically coupled quantum dots

❖ Two vertically coupled dots

Result for: $R = 6nm$, $d = 6nm$ and $d_d = 3.6nm$

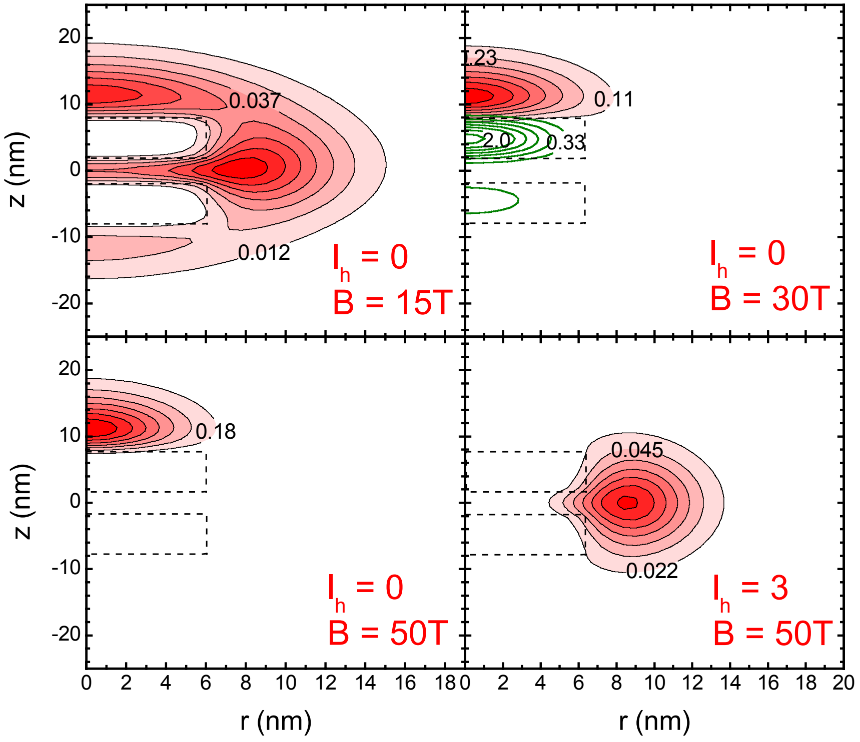


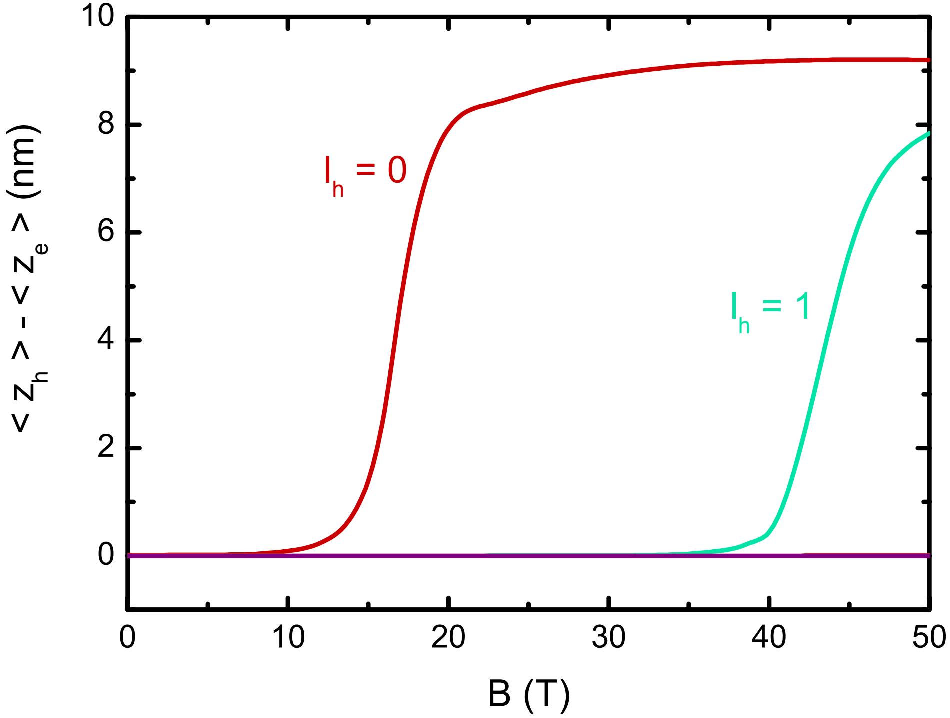


- ❖ extra parameter to vary: interdot-distance d_d
- ❖ easier realization of the pillar-like system

Spontaneous symmetry breaking

- enhancement of the Coulomb attraction
- *magnetic field induces a permanent dipole moment*



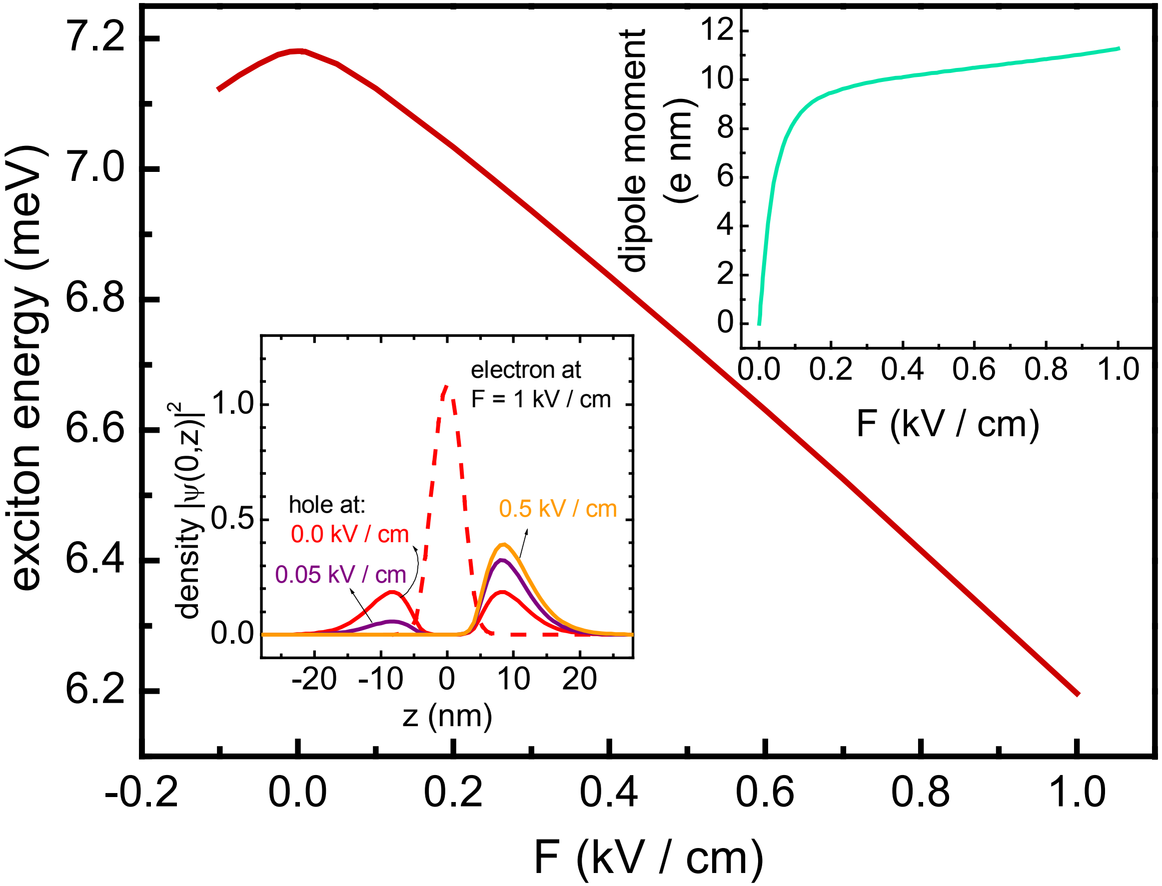


Stark effect

Single and coupled type-II dots

❖ Single type-II disk

R = 10nm, d = 8nm

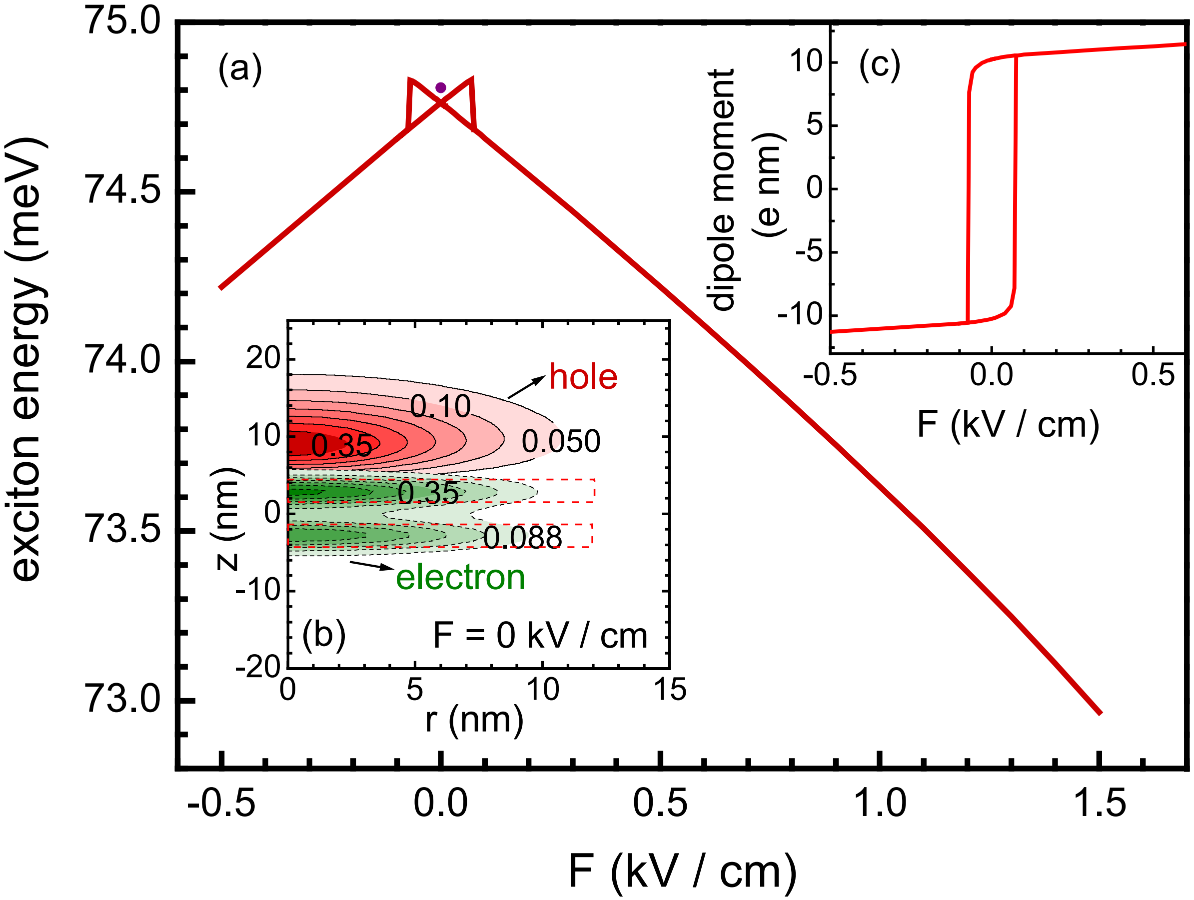


- ❖ non-parabolic Stark shift (cfr. coupled type I disks)
- ❖ creation of a strong dipole moment for $F \neq 0$
- ❖ linear contribution is more important

$$E(F) = E(F_0) - p(F - F_0) - \beta(F - F_0)^2$$

Two coupled type II-disks

$R = 12nm,\ d = 3nm,\ d_d = 3nm$



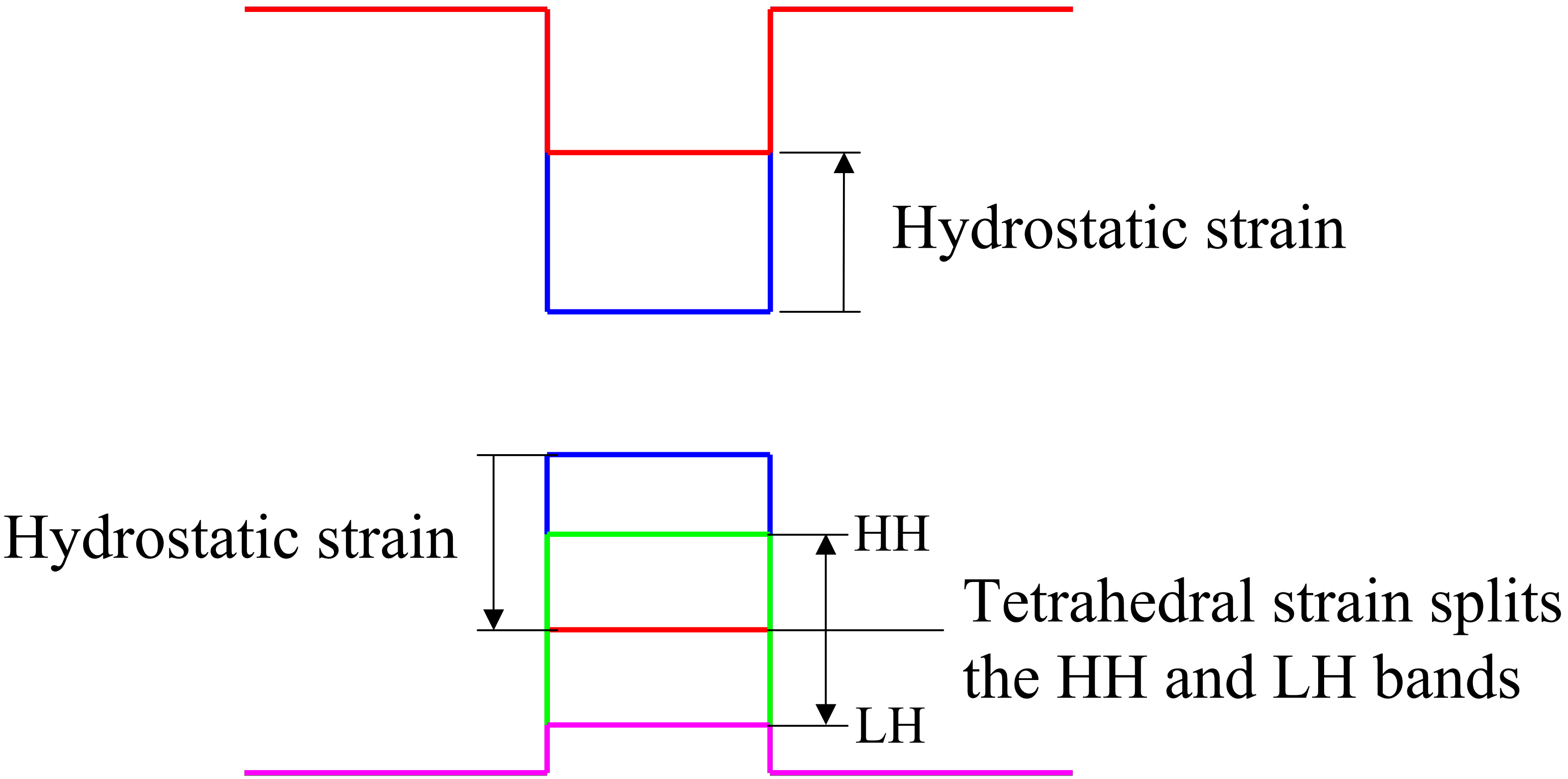
- hysteresis due to spontaneous symmetry breaking
- system is trapped in the energy minimum
- permanent dipole moment

Effects due to strain

Hole band engineering

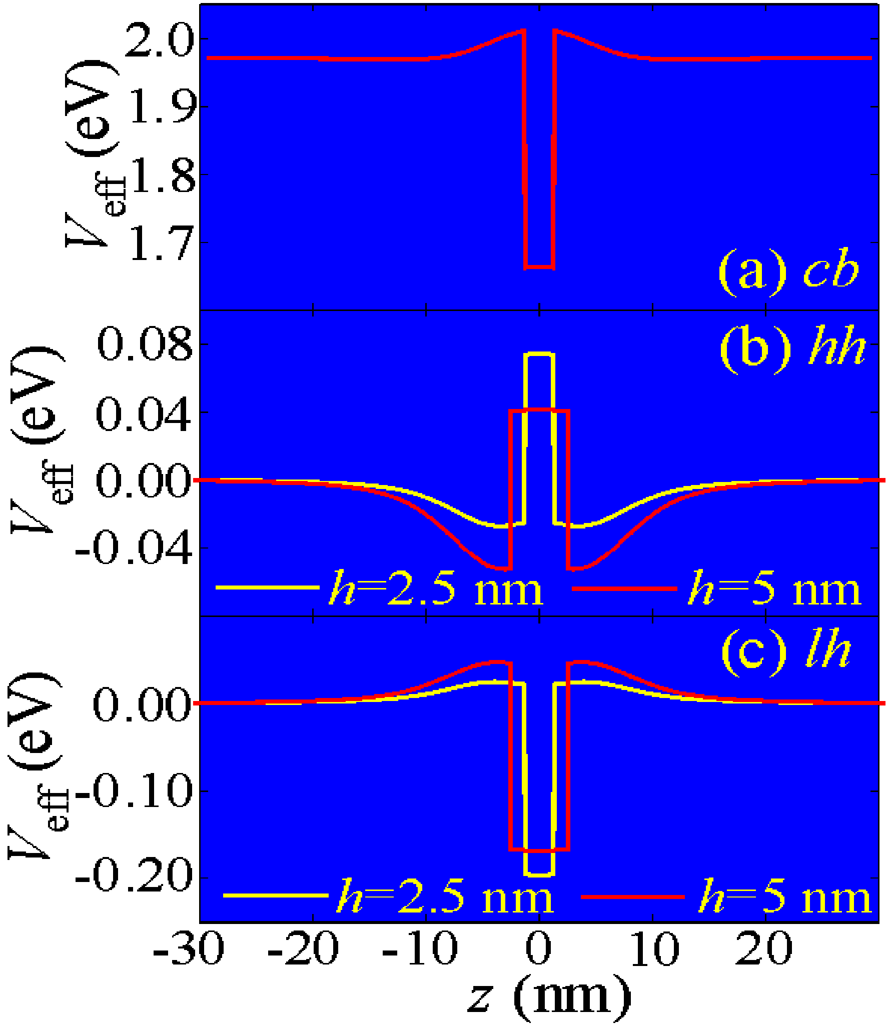
Pseudomorphic quantum wells:

case of compressive strain



Tetrahedral strain splits the HH and LH bands

The effective potentials: for different SAQD’s height



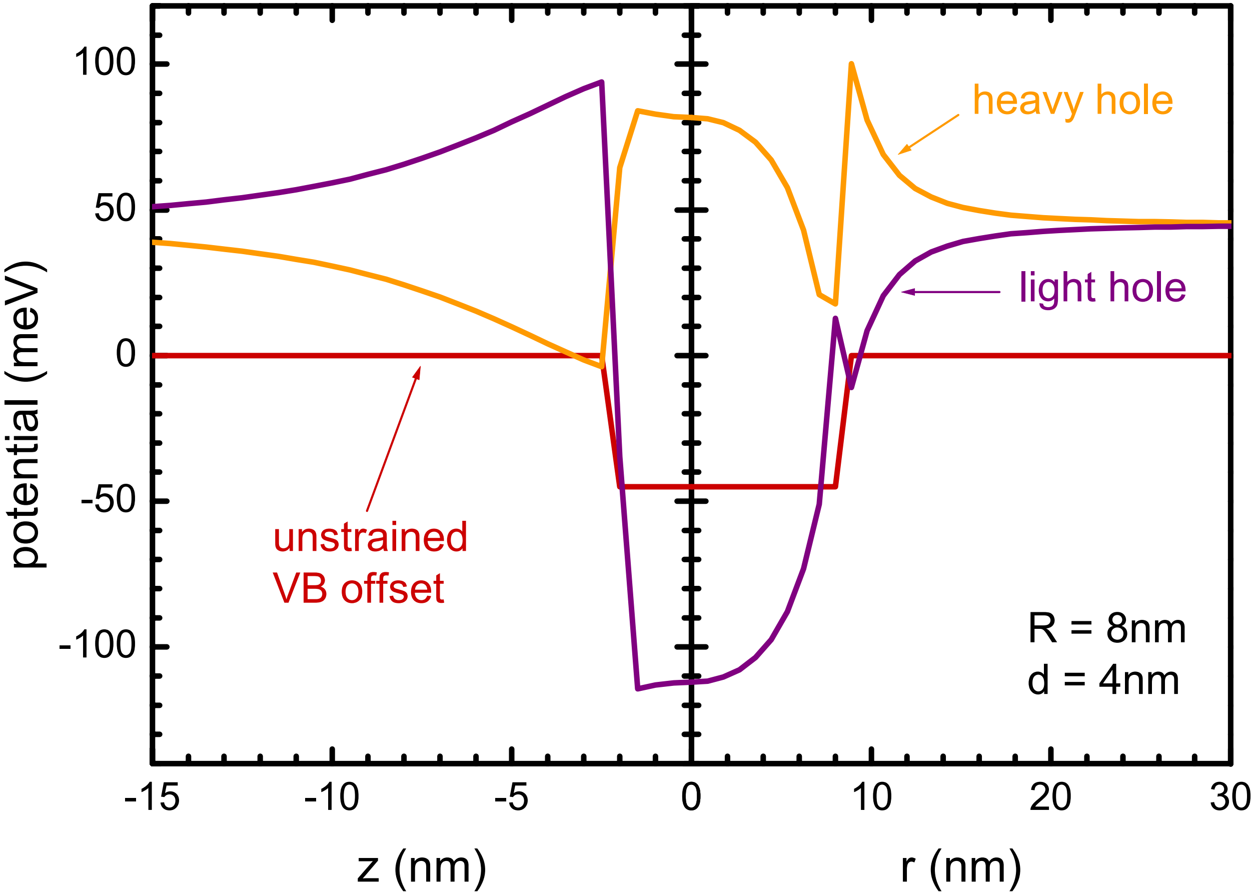
InP/$In_{0.49}Ga_{0.51}P$

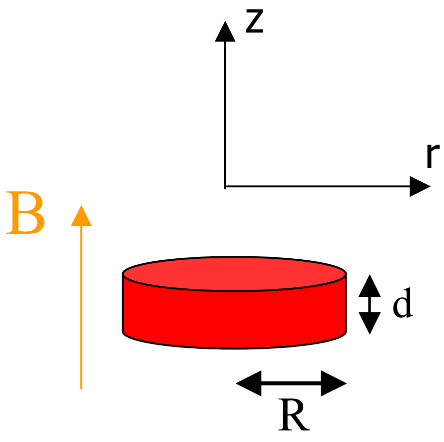
Conduction band

Heavy hole band

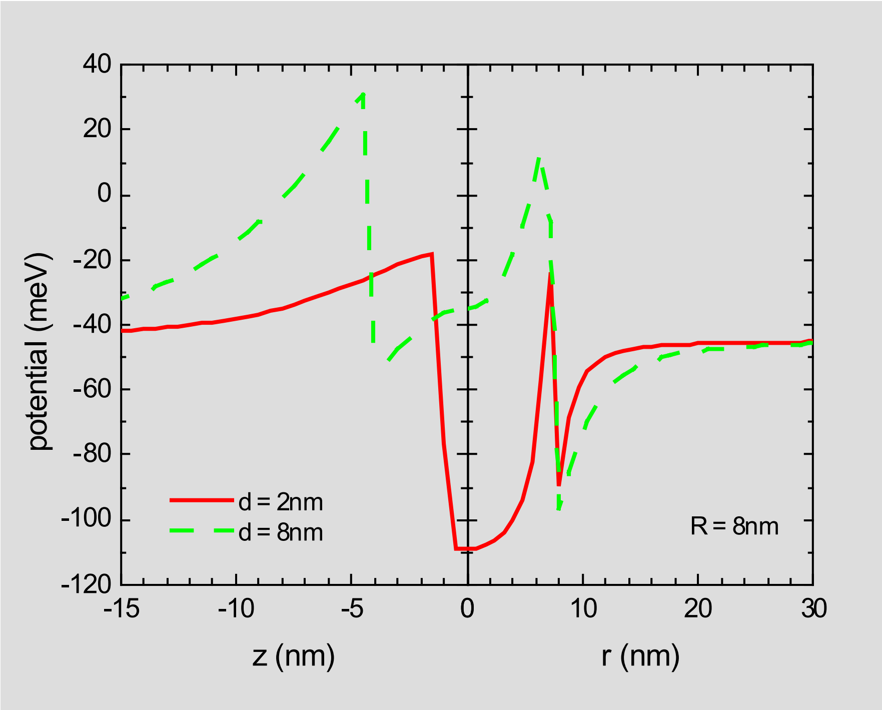
Light hole band

Effective potentials

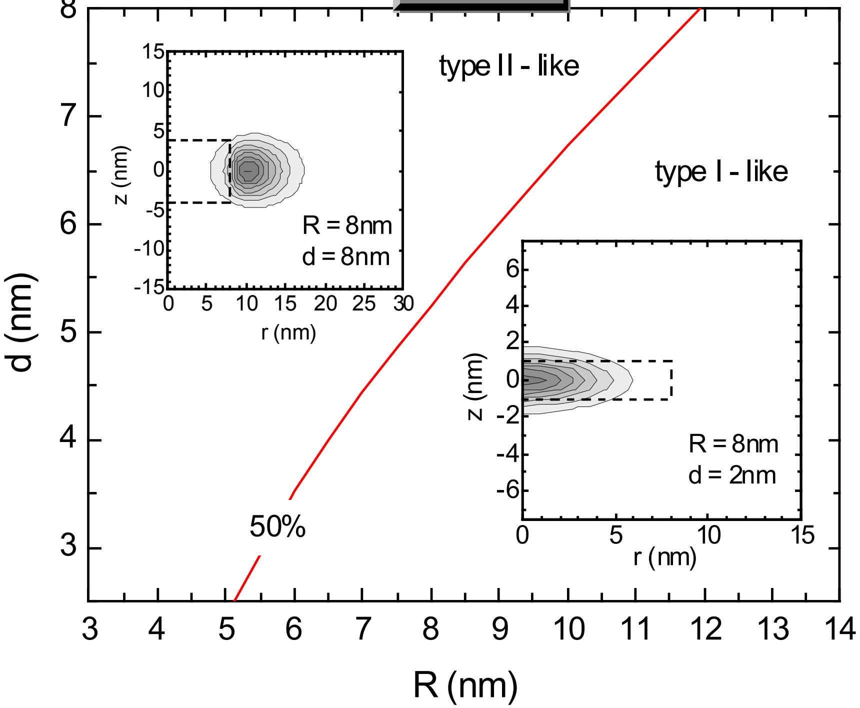




Heavy hole: type I → type II

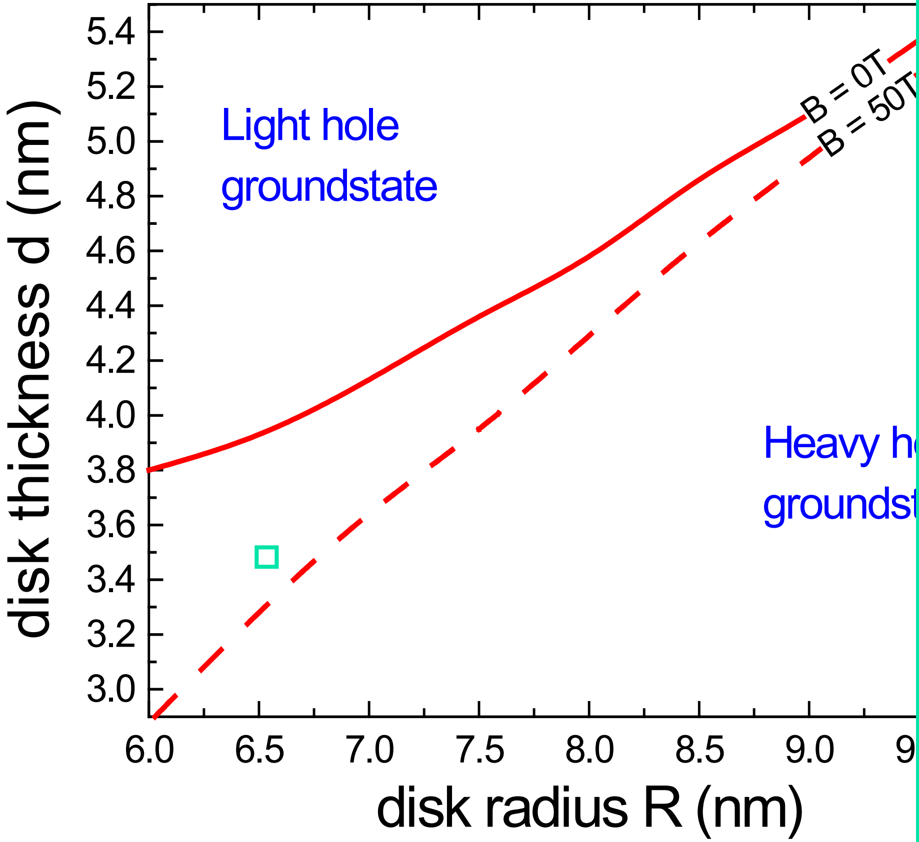


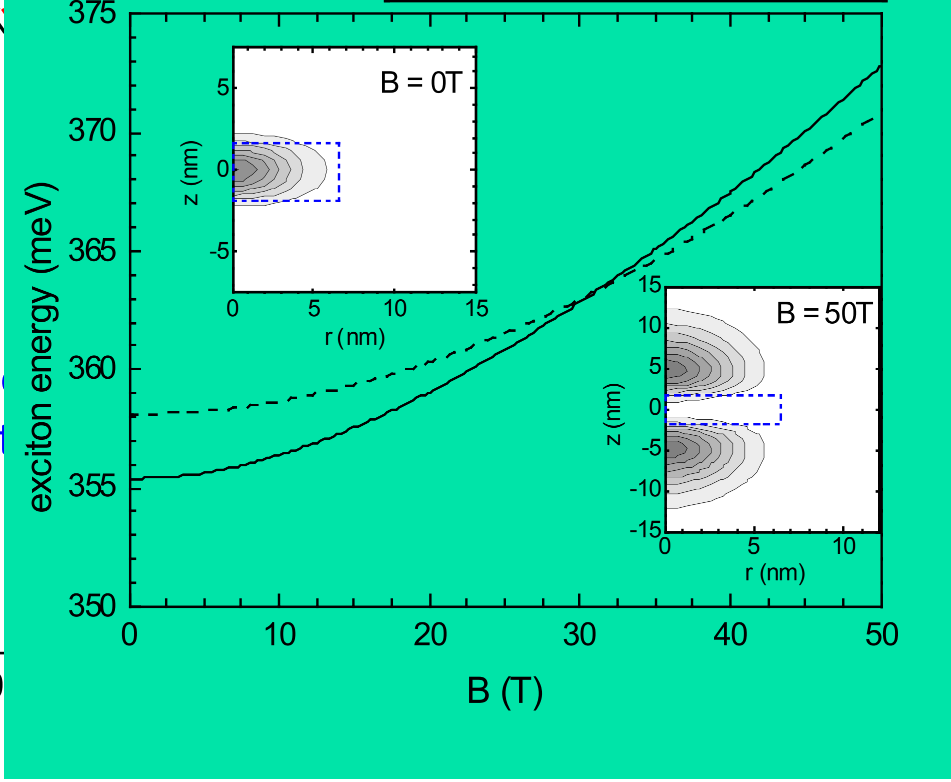
Heavy hole



Heavy – light hole transition

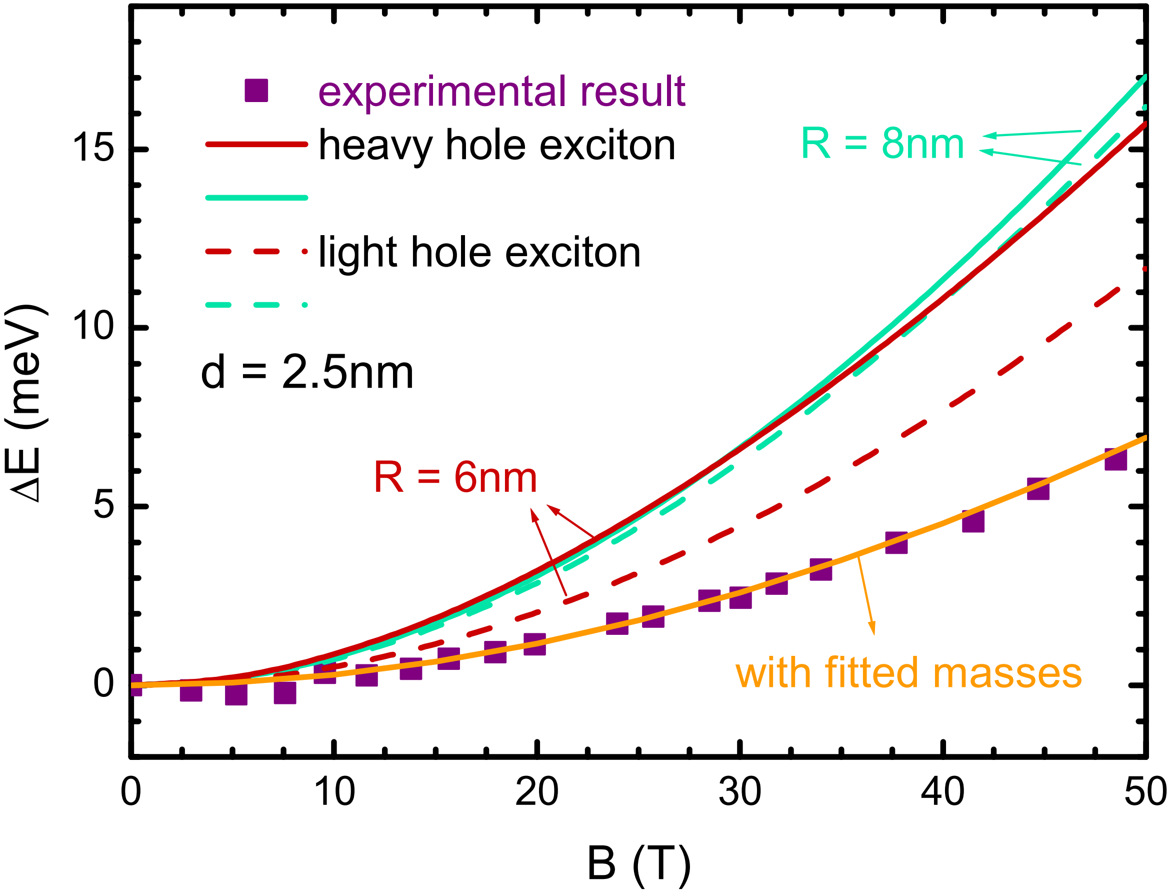
Mass (m_o)	z	$\parallel$
hh	0.61	0.15
lh	0.12	0.30





Comparison with experiment[1]

Diamagnetic shift: $\Delta E = E(B) - E(B = 0T)$



- influence of radius?
- influence of masses?

Fitted masses:

$$m_e = 0.15m_0 \leftrightarrow 0.077m_0$$

$$m_{hh,\square} = 0.5m_0 \leftrightarrow 0.1515m_0$$

$$m_{lh,\square} = 1.5m_0 \leftrightarrow 0.269m_0$$

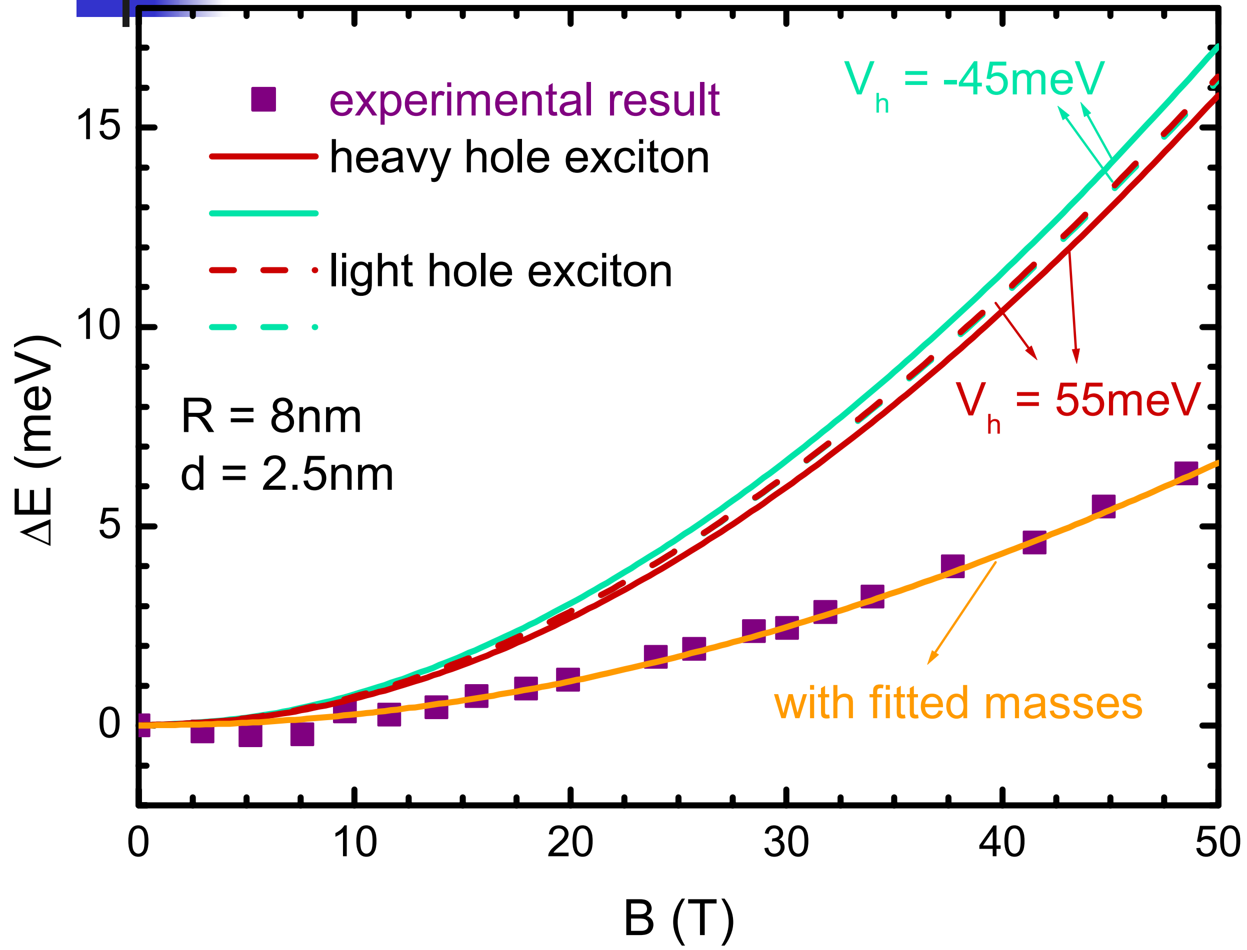
[1] M. Hayne, R. Provoost, M.K. Zundel, Y.M. Manz, K. Eberl, V.V. Moshchalkov, Phys. Rev. B **62**, 10324 (2000).

Start with a positive unstrained VB offset[1]

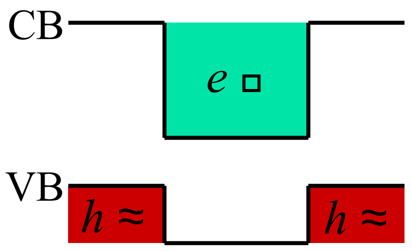
⇒ Still discrepancy between theory and experiment

⇒ increase of the masses needed to obtain good fit

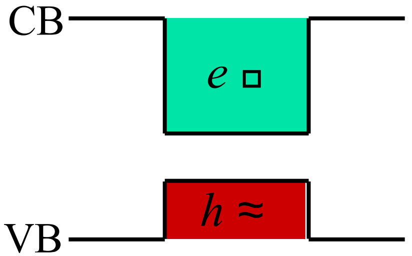
$$m_e = 0.15 m_0 \ ; m_{hh,\square} = 0.5 m_0 \ ; m_{lh,\square} = 1.5 m_0$$



Negative offset



Positive offset



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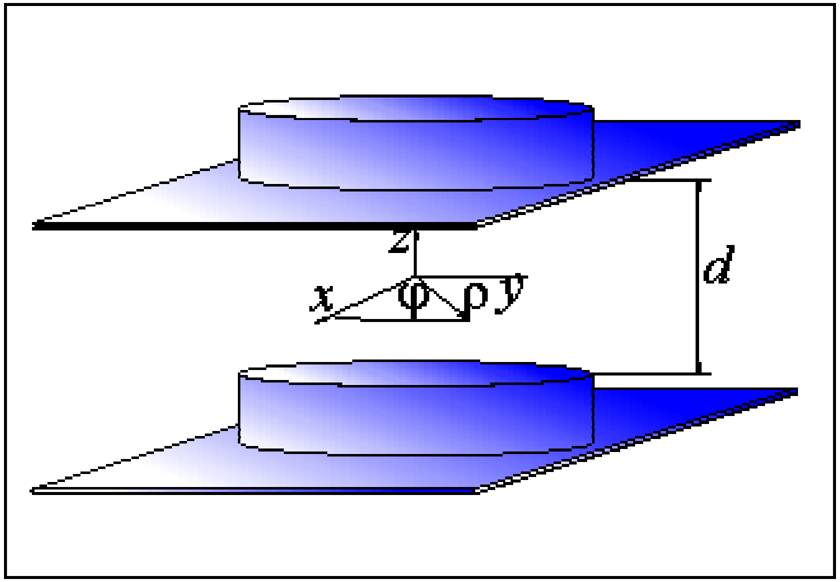
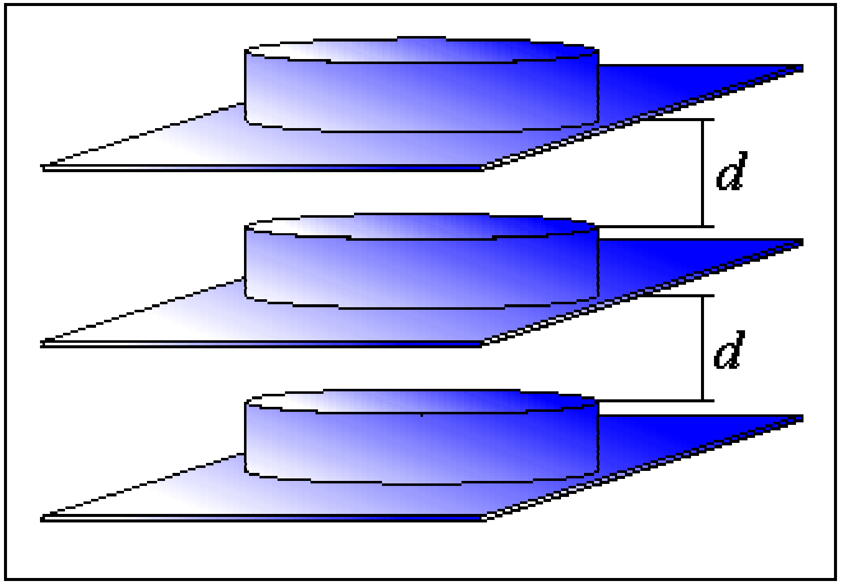
[1] S.-H. Wei and A. Zunger, Appl. Phys. Lett. **72**, 2011 (1998)

Coupled cylindrical SAQD’s



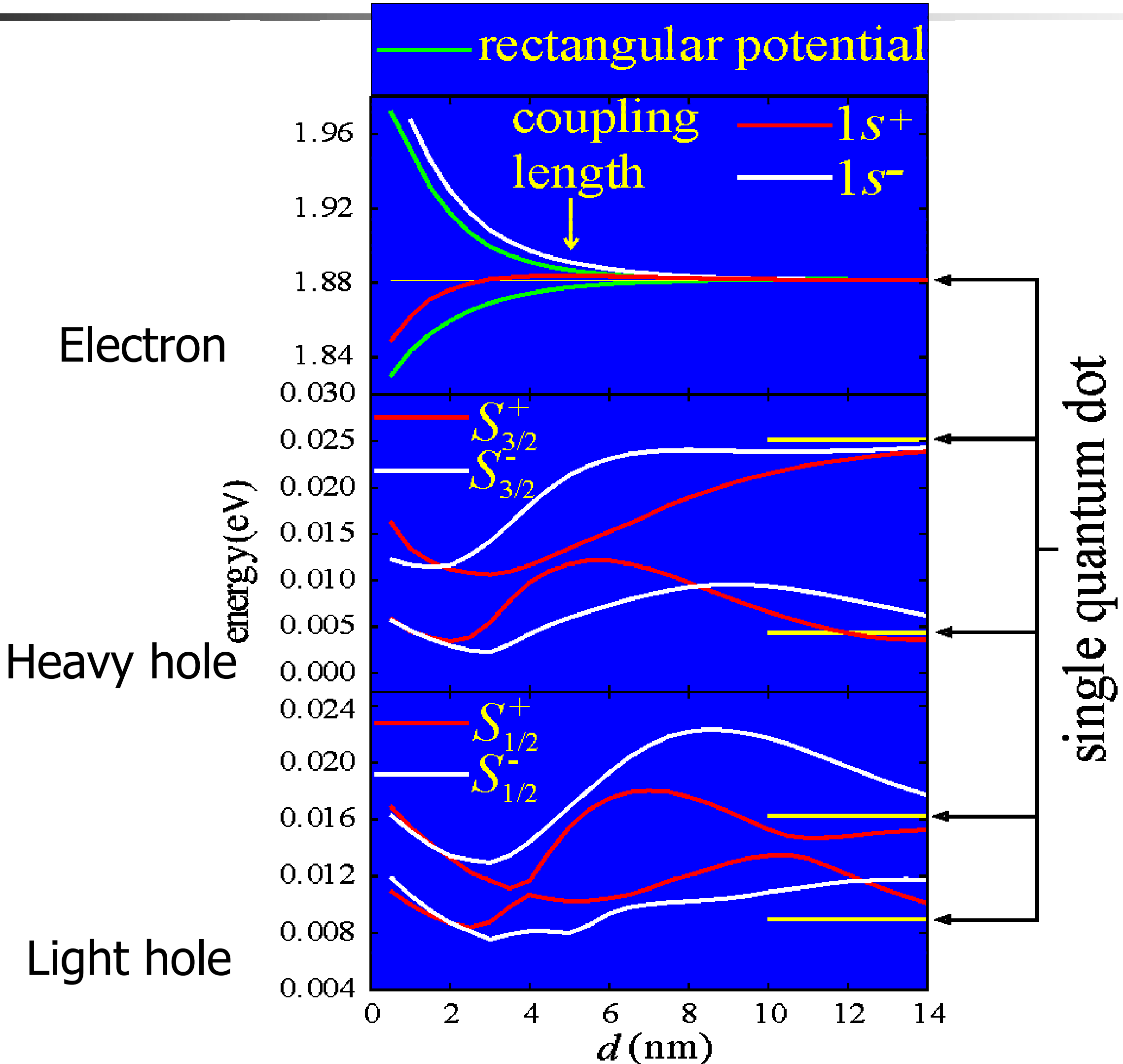
Two-dot stack



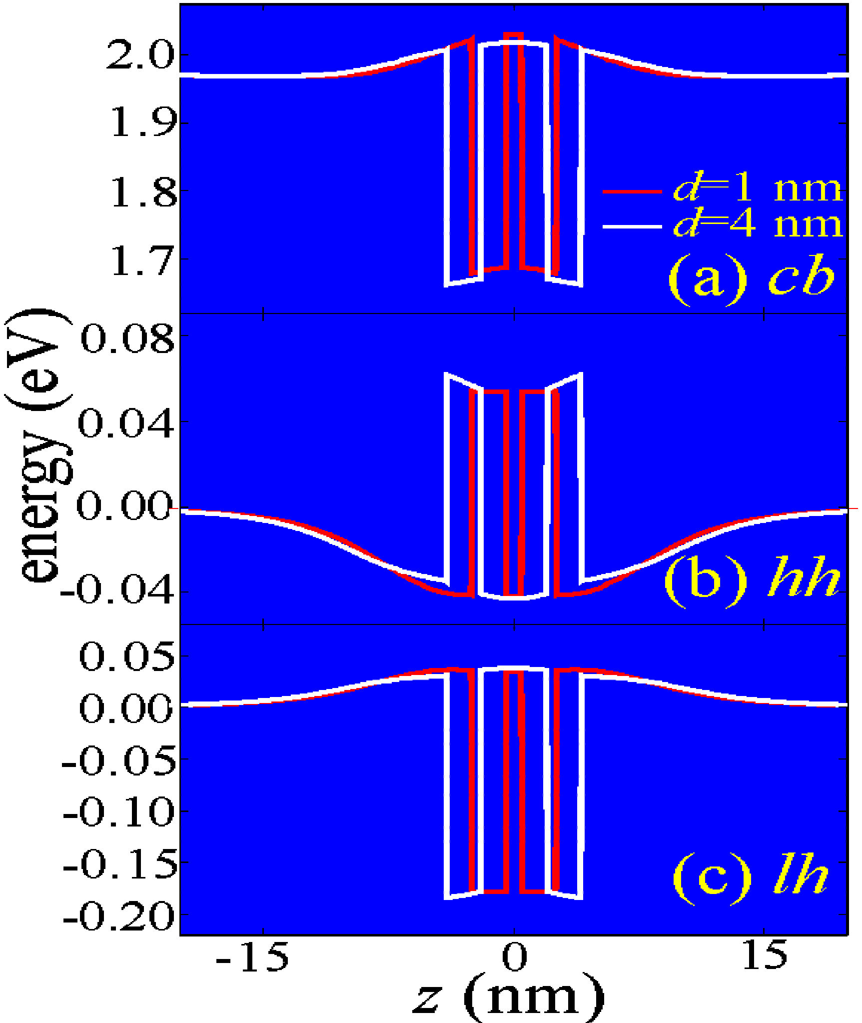
Three-dot stack

Energy levels in vertically coupled quantum dots

R=8nm
h=2nm



Effective potentials in two vertically coupled quantum dots



Conduction band

Heavy hole band

Light hole band

Hole states

$F_z=J_z+L_z=f\hbar$: total angular momentum

$J_z=j\hbar$: Bloch part

$L_z=l\hbar$: envelope part

|f|=3/2 :

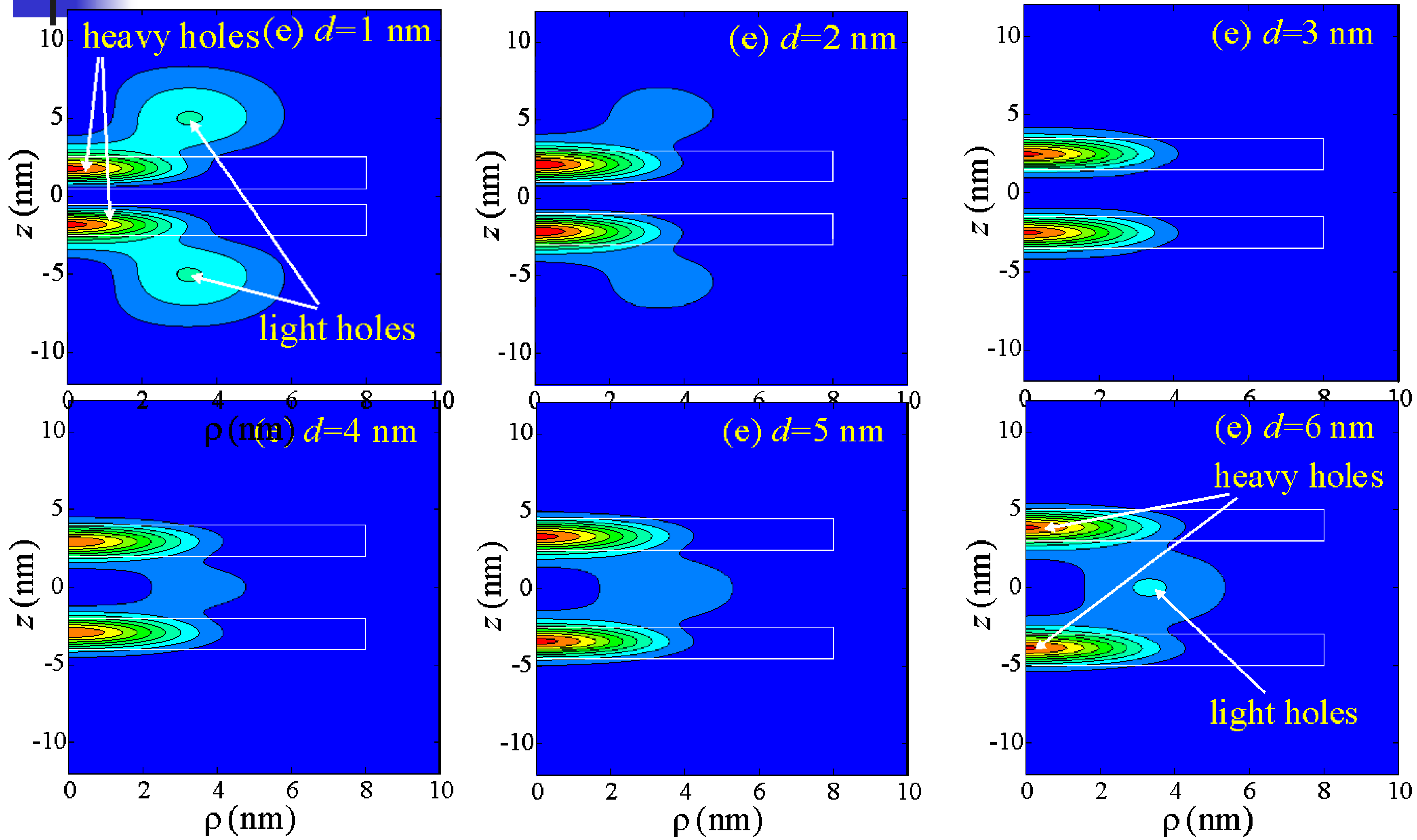
Heavy hole (j=3/2), l=0,-3
Light hole (j=1/2), l=-1, -2

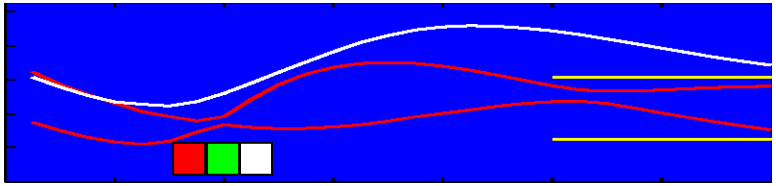
|f|=1/2 :

Heavy hole (j=3/2), l=-1,-2

Light hole (j=1/2), l=0,-1

Probability density of the odd $S_{3/2}$ state in the two-dot stack (ground state for d>2 nm)





Ground

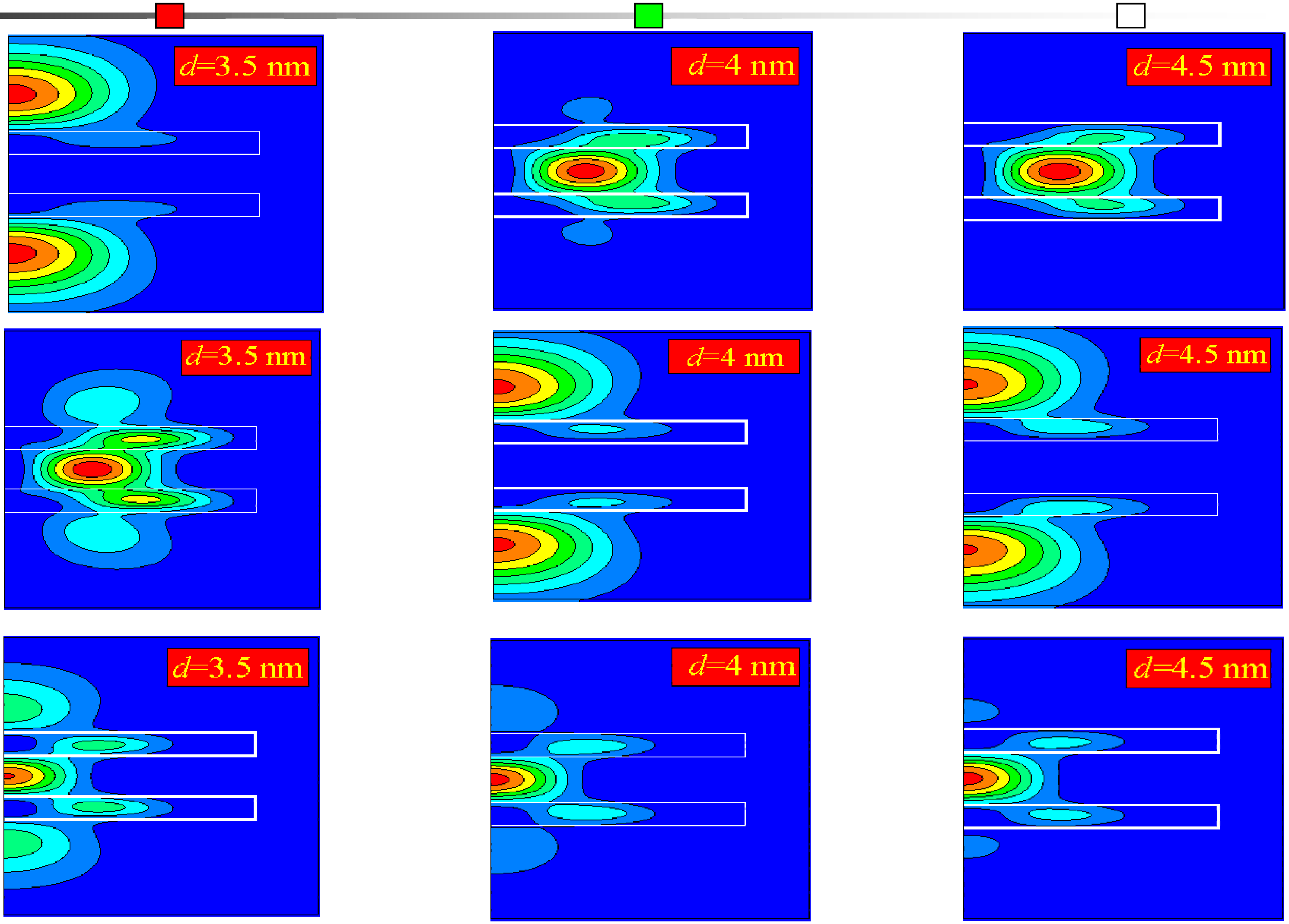
$S^{+}_{1/2}$

Second

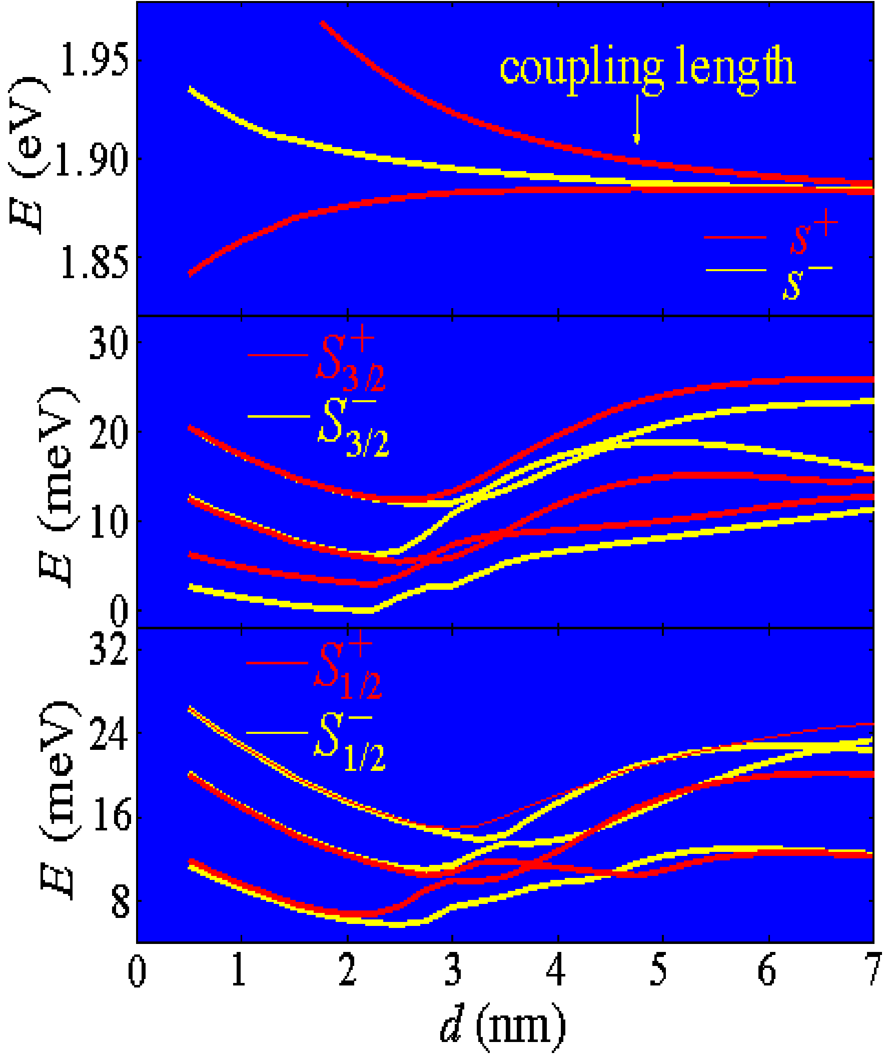
$S^{+}_{1/2}$

Ground

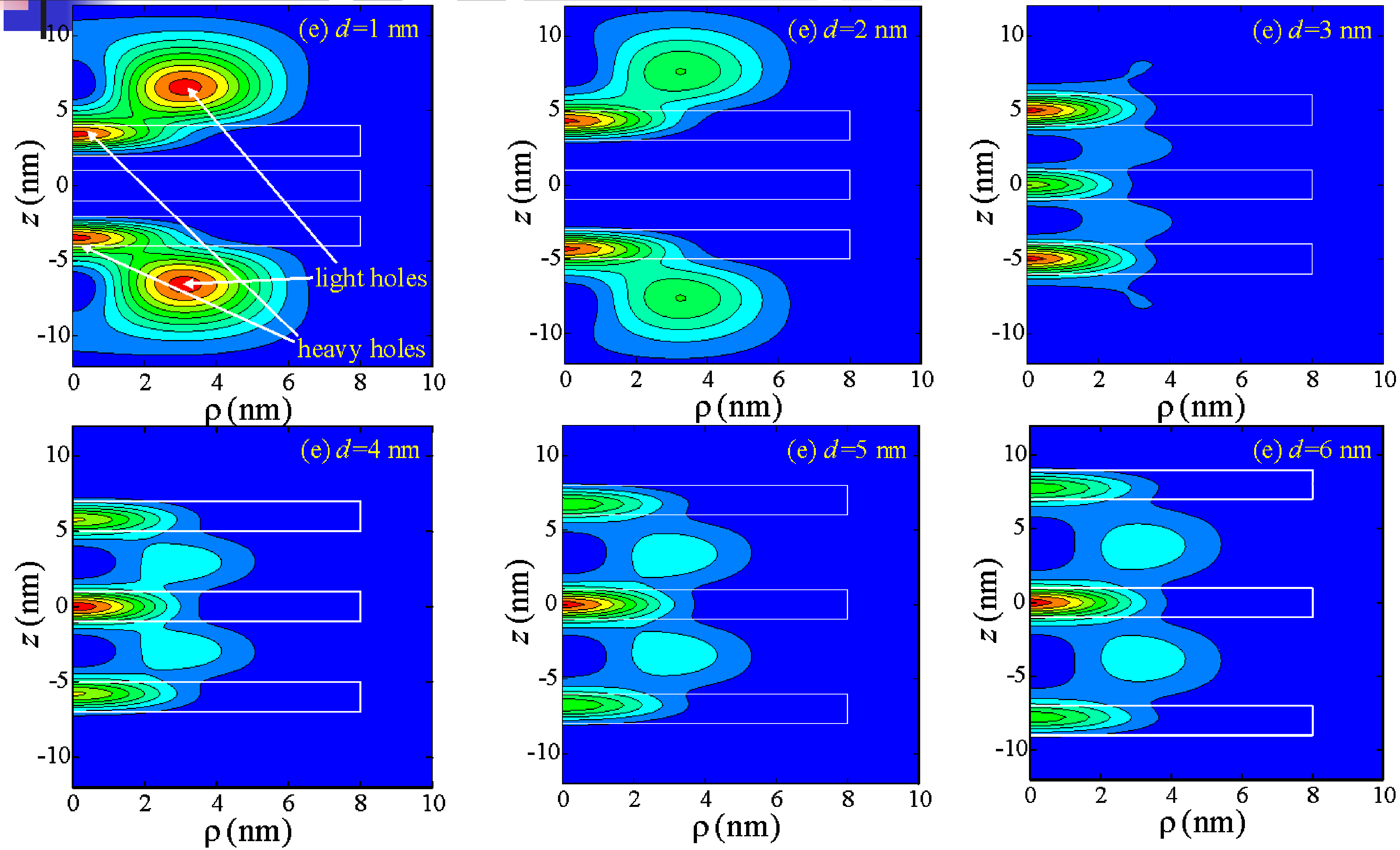
$S^{-}_{1/2}$



Energy levels in a three-dot stack



Probability density of the even $S_{3/2}$ state in the three-dot stack (ground state for d>2 nm)

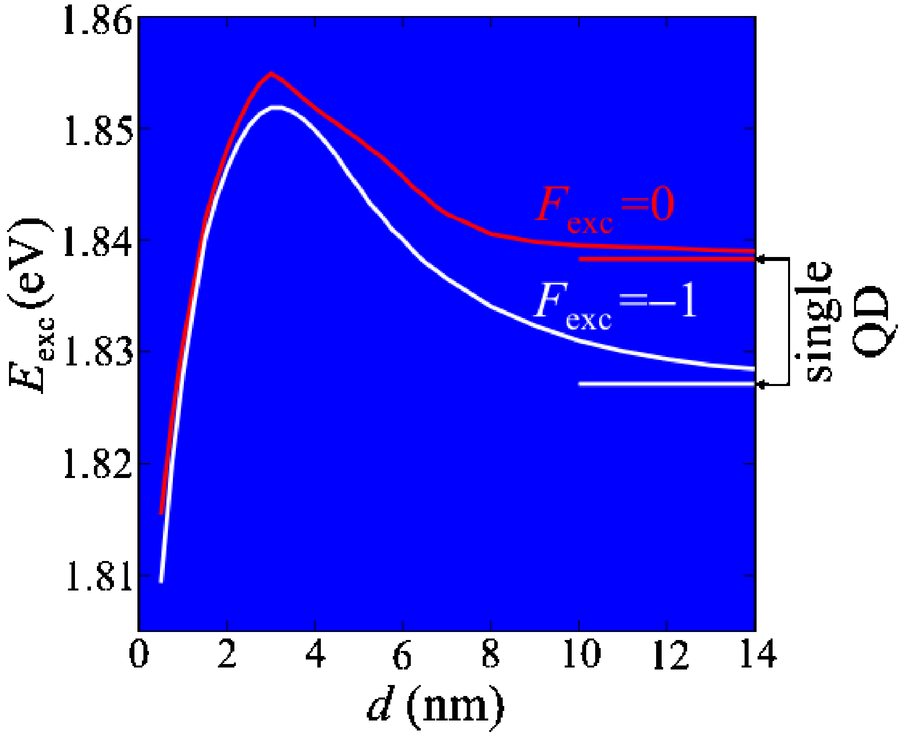


Excitons in the two-dot stack

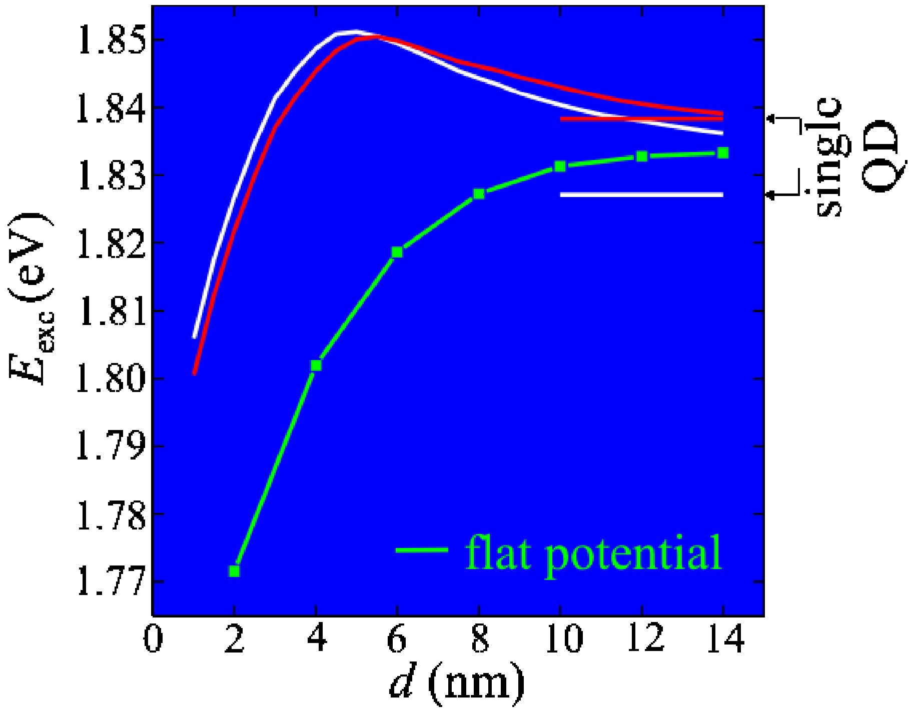
Dependence of the ground states for F_{exc}=-1 and F_{exc}=0 on the spacer thickness (h=2nm; r=8nm).

F_{exc}=-1 (heavy-hole-like exciton)

F_{exc}=0 (light-hole-like exciton).



Three-dot stack



There appears substantial overshoots in the exciton energies.

Conclusions (1/2)

- Exciton in a type II quantum dot: pillar – disk systems
- Magnetic field effect:
  - disk-like system: parabolic -> linear increase of energy with B (Cfr. Type I)
  - pillar-like system: angular momentum transitions

    vertically coupled dots with small interdot distance

    spontaneous symmetry breaking -> magnetic field induced dipole moment
- Electric field effect: Stark shift
  - Parabolic field dependence only for single type-I disk
  - Strongly linear dependence for coupled type-I and single and coupled type II disks -> creation of dipole moment

Conclusions (2/2)

- Strain effect: hole band engineering (light – heavy hole).

- The total angular momentum of the ground state of holes changes with the thickness of the quantum dot.

- In coupled quantum dots: strain acts opposite to quantum mechanical coupling. It increases the electron ground state above the single quantum dot value.

  - Electron coupling is effective only for spacers thinner than the *coupling length.*

  - Holes exhibit 'electronic' coupling only for very thin spacers.

- Strain predominantly influences the "holes". Therefore, our simple model calculation will be more appropriate for e.g. GaSb/GaAs and InAs/Si dots.

The end

For details see: http://cmt.uia.ac.be

- *Magnetoexcitons in planar type-II quantum dots in a perpendicular magnetic field*
  K.L. Janssens, B. Partoens, and F.M. Peeters, Phys. Rev. B **64**, 155324 (2001).
- *Single and vertically coupled type-II quantum dots in a perpendicular magnetic field: exciton grounstate properties*
  K.L. Janssens, B. Partoens, and F.M. Peeters, Phys. Rev. B **66**, 075314 (2002).
- *Stark shift in single and vertically coupled type-I and type-II quantum dots*
  K.L. Janssens, B. Partoens, and F.M. Peeters, Phys. Rev. B **65**, 233301 (2002).
- *Effect of isotropic versus anisotropic elasticity on the electronic structure of cylindrical* $InP/In_{0.49}Ga_{0.51}P$ *self-assembled quantum dots*
  M. Tadić, F.M. Peeters, and K.L. Janssens, Phys. Rev. B **65**, 165333 (2002).
- *Strain and band edges in single and coupled cylindrical InAs/GaAs and InP/InGaP self-assembled quantum dots*
  M. Tadić, F.M. Peeters, K.L. Janssens, M. Korkusiński, and P. Hawrylak,
  J. Appl. Phys. **92**, 5819 (2002).
- *Electronic structure of the valence band in cylindrical strained InP/InGaP quantum dots in an external magnetic field*
  M. Tadić and F.M. Peeters, Physica E **12**, 880 (2002).
- *Electron and hole localization in coupled InP/InGaP self-assembled quantum dots*
  M. Tadić, F.M. Peeters, B. Partoens, and K.L. Janssens, Physica E **13**, 237 (2002).