Reengineering the Optics of Quantum Dots Using Nanomechanical Strain

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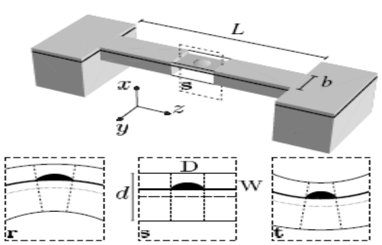
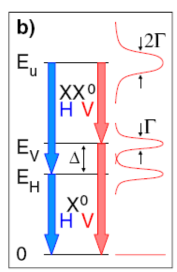
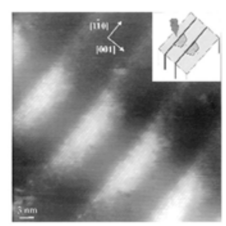
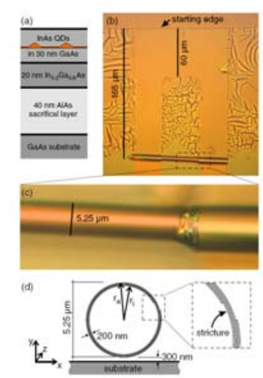








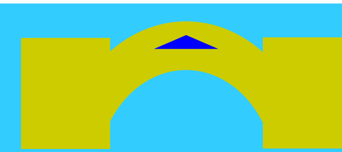
Introduction

Passive control of quantum dot (QD) optics is achieved by tailoring QD size, shape and composition during growth. ***Dynamical control of excitons in QDs is highly desirable.*** For QDs embedded in nanomechanical structures, ***dynamical control could be obtained by using externally imposed mechanical strain to reengineer the QDs to modify level degeneracies, polarize optical transitions, induce entanglement, or change coupling between closely spaced dots,*** all capabilities needed to use dots in optical nanodevices and quantum information processing.

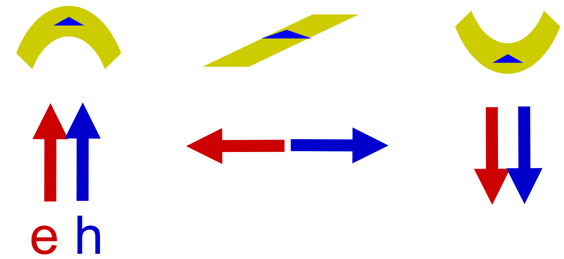
To exploit hybrid nanomechanical/QD devices, ***an understanding of the coupling between internal strain due to lattice mismatch, externally imposed mechanical strain, and excitons in the QDs in the nanomechanical structure is needed.***

To identify the effects of mechanical strain, we present a theory of InAs QDs in a GaAs nanomechanical bridge. The bridge is bent to simulate external strain applied to reengineer the QDs.

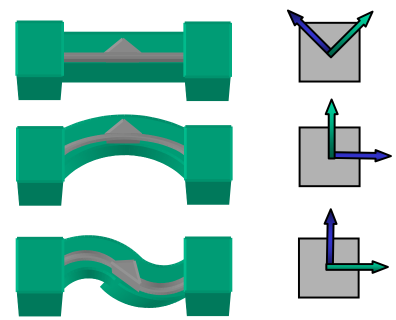
Nanomechanically Strained QDs: Summary



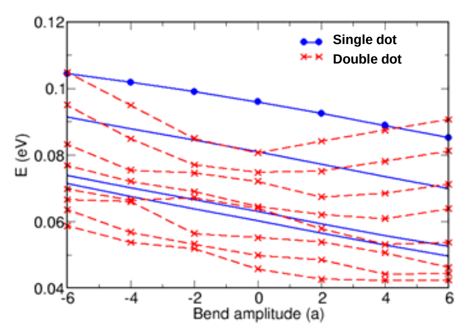
- DC Stark field analog
  - Biaxial deformation acts like an electric field E_z
    - Electrons and holes shift the same way
  - Shear bends act like E_x
    - Electrons and holes shift the opposite way
  - Internal relaxation and state distortion is critical



- Excitons
  - Strain reengineers the anisotropic exchange coupling
  - This controls the phase of spin mixing in the exciton, leading to
  - Fine structure level mixing and crossing and polarization rotation



- Coupled dots
  - Strain-induced state crossing and inter-dot transfer

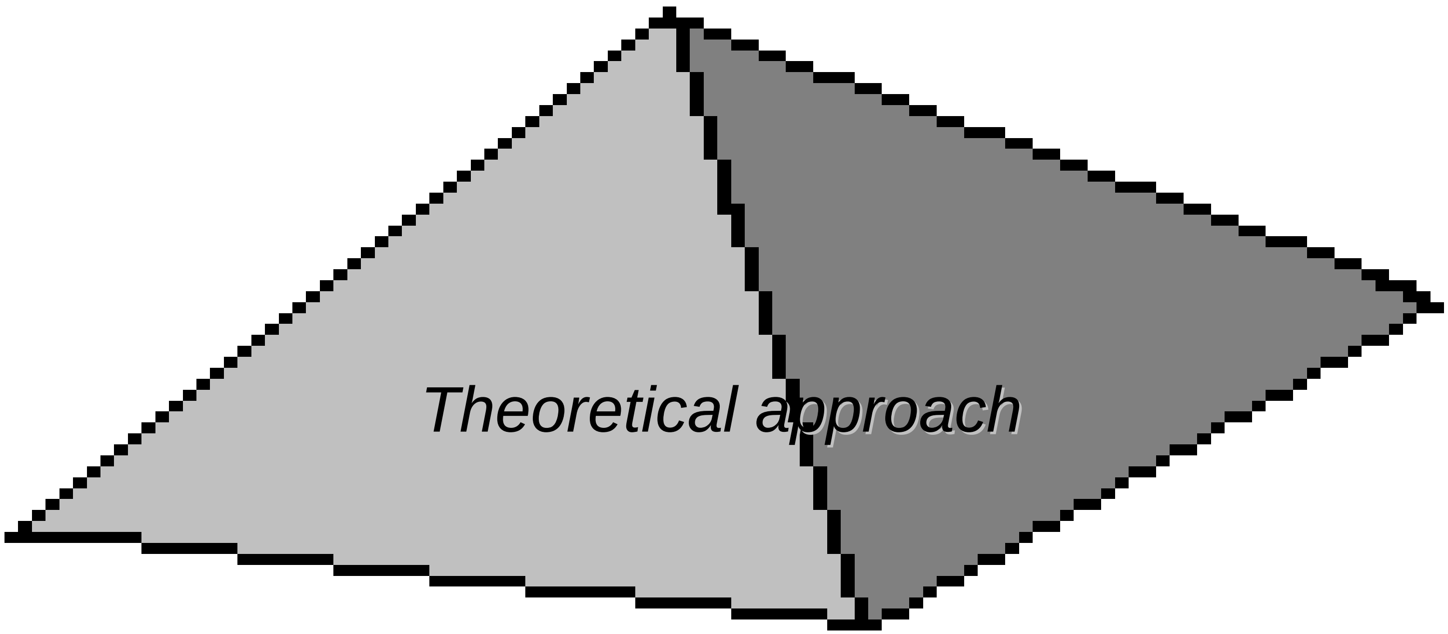


Theory of QDs in nanomechanical oscillators:

Results for a pyramidal InAs QD in a GaAs nanobridge

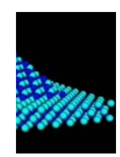
Geometries and applied strain

Symm



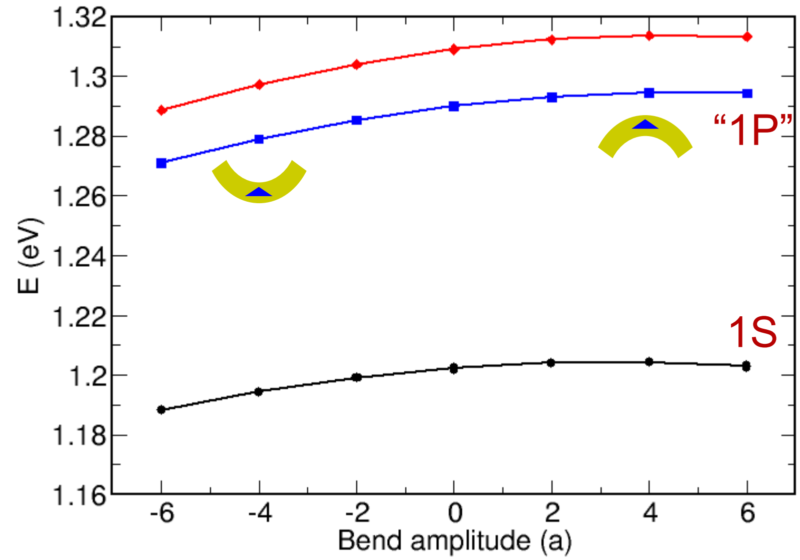
Theoretical approach

- at
- la
- ex
- in
- excitons: configuration interaction approach



Manipulating electron energies with nanomechanical strain

Electrons

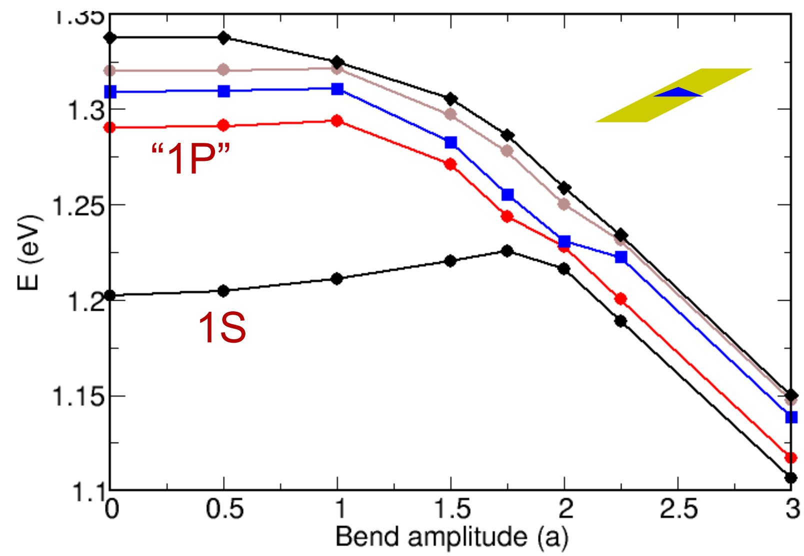


Biaxial deformation

•"Rigid" shift with fixed level ordering and state symmetries

•Shift: 1-10 meV

•Electron and hole shift the same way



Shear

•Quadratic increase

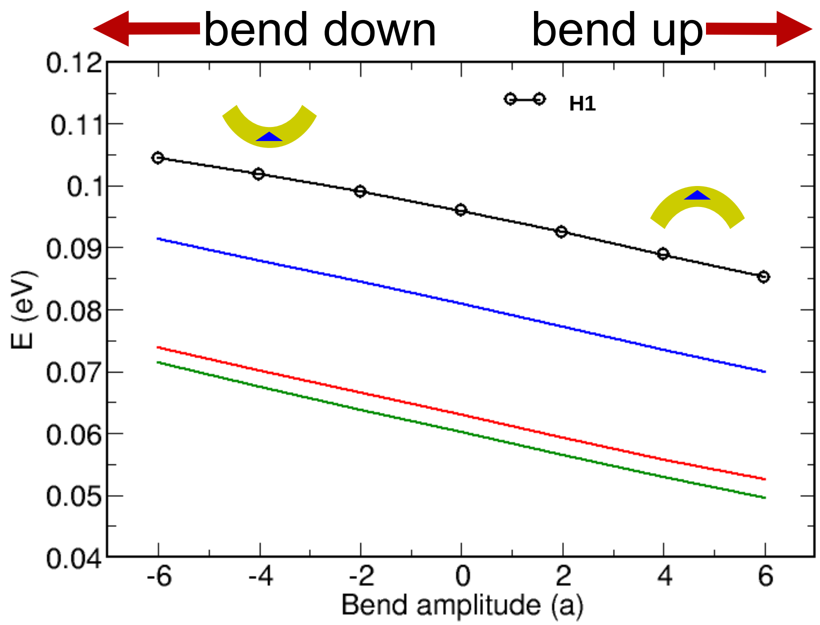
•Mixing, pushed into the wetting layer

•Electron and hole shift the opposite way

"Analog" to DC Stark effect with same or opposite charge for e and h

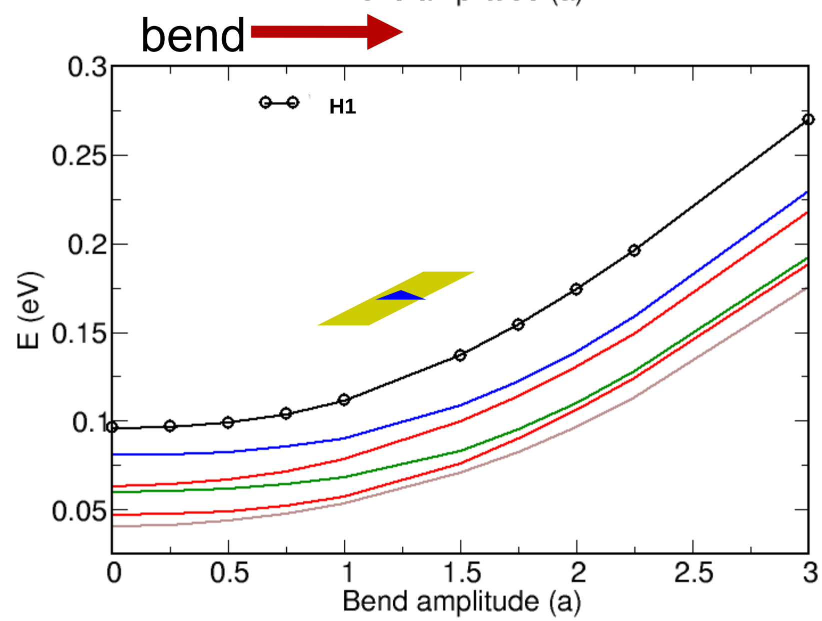
Manipulating hole energies with nanomechanical strain

Holes



Biaxial deformation

- “Rigid” shift with fixed level ordering and state symmetries
- Electron and hole shift the same way

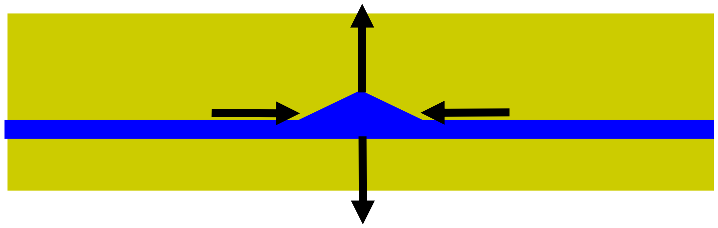


Shear

- Quadratic decrease
- Mixing

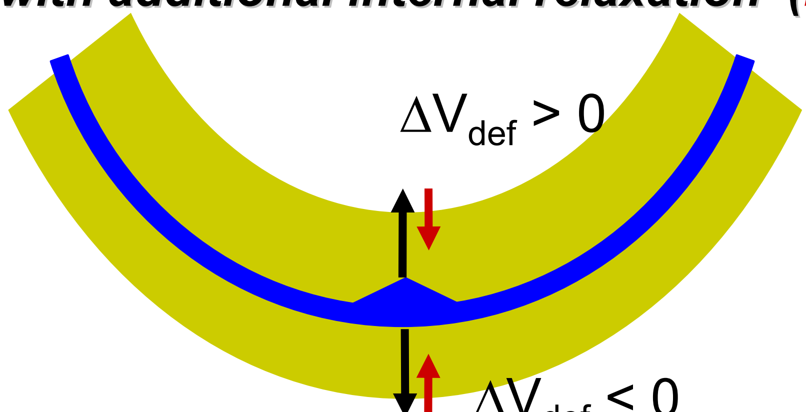
Internal relaxation determines level and charge shifts

Biaxial lattice relaxation in a flat bridge

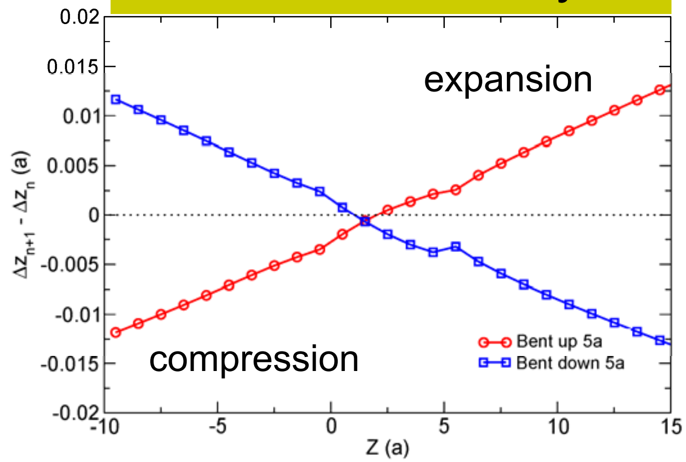


Lattice relaxation in a bent bridge

with additional internal relaxation (red)

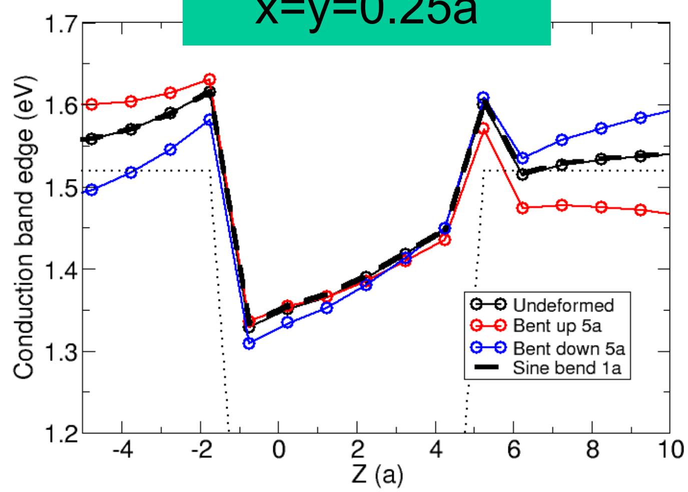


δZ lattice shift: x=y=0



Conduction band profile

x=y=0.25a

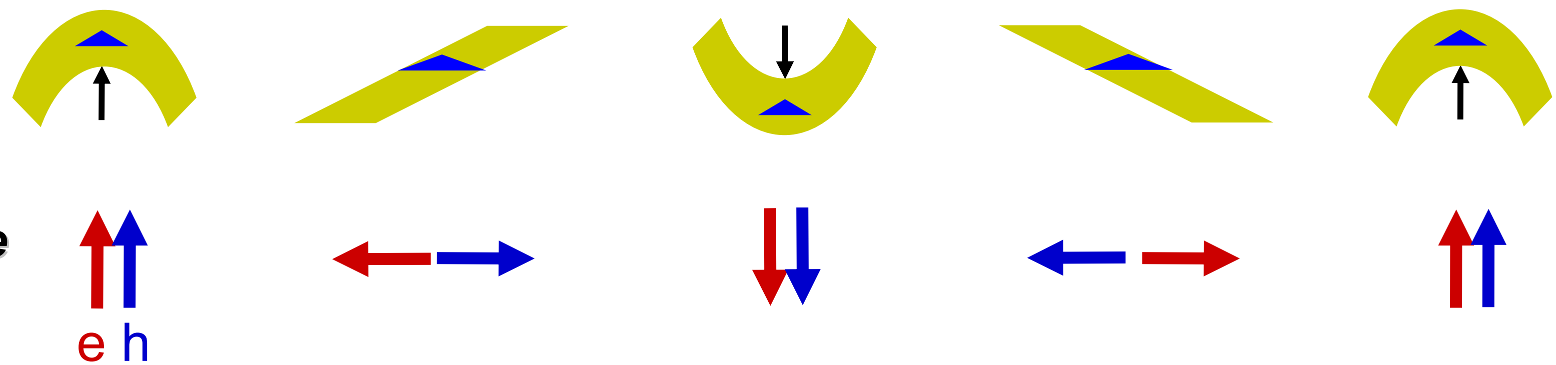


Distorting the electron and hole states

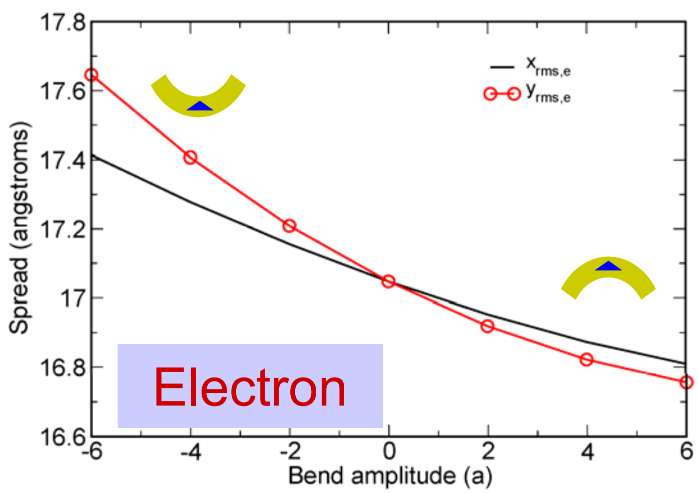
Strain-induced charge shifts:"analog" to Stark effect with counterrotating e and h

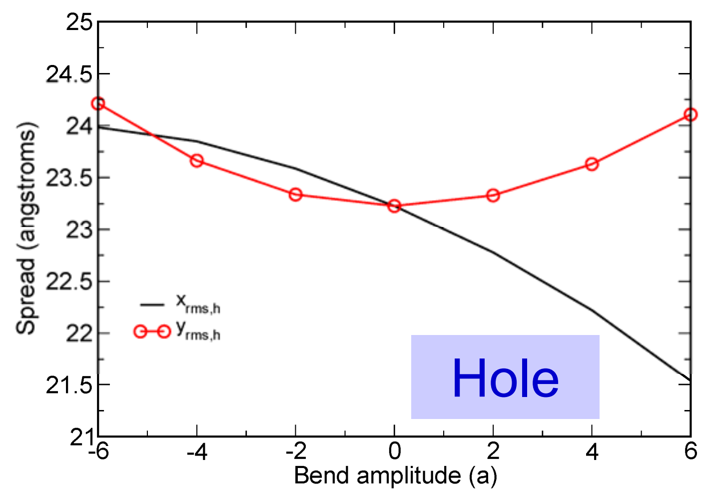
Bend

Charge shift



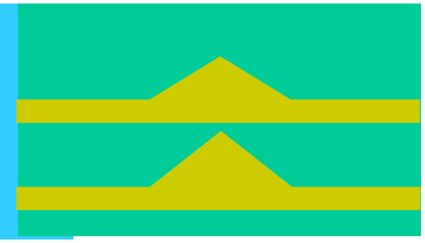
Asymmetric stretching or squeezing





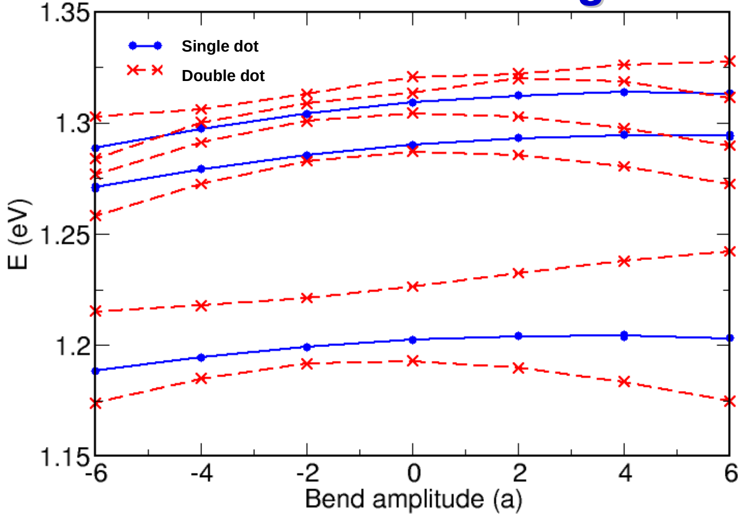
Manipulating inter-dot transfer

Example: electrons in a biaxially deformed double dot



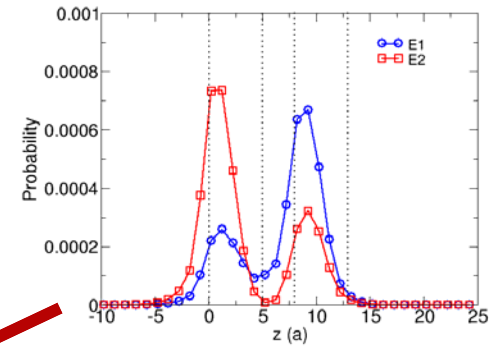
Strain-induced charge shifting determines charge transfer in coupled dots

Level crossing

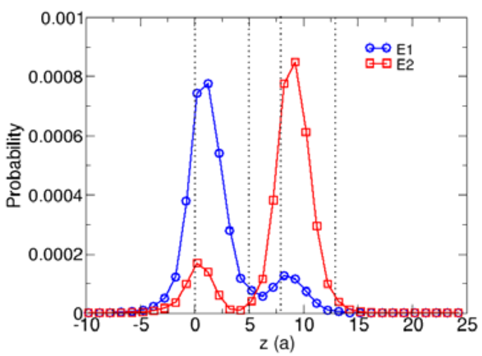


Charge transfer

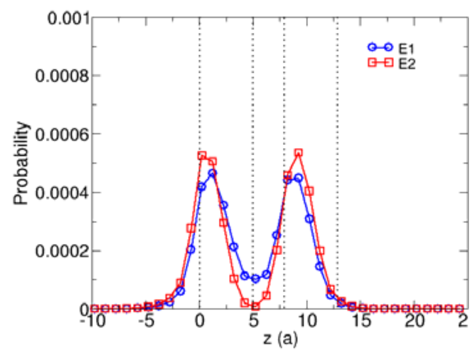
Flat



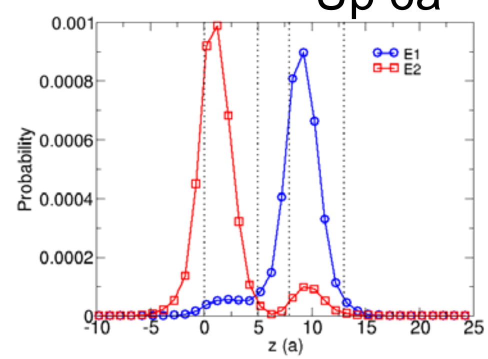
Down 6a



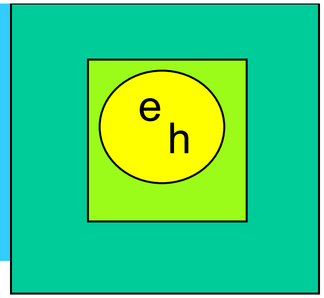
Down 2a

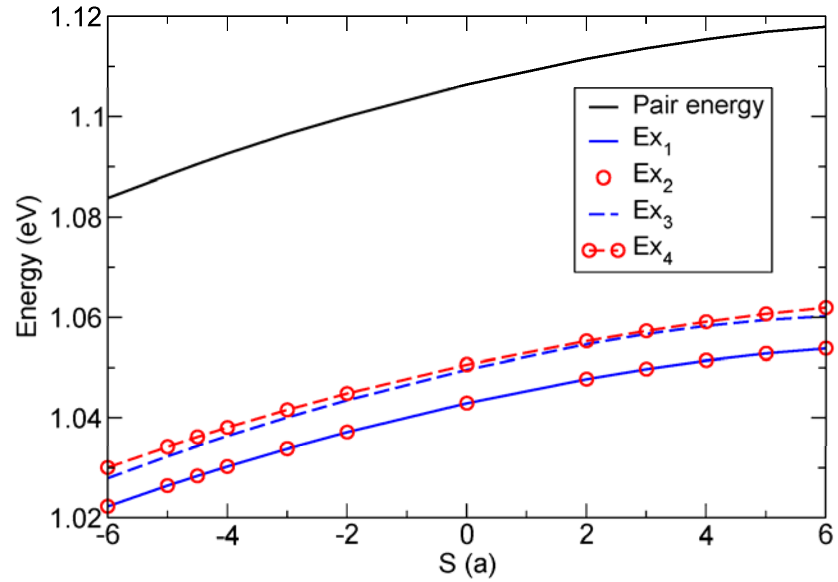


Up 6a



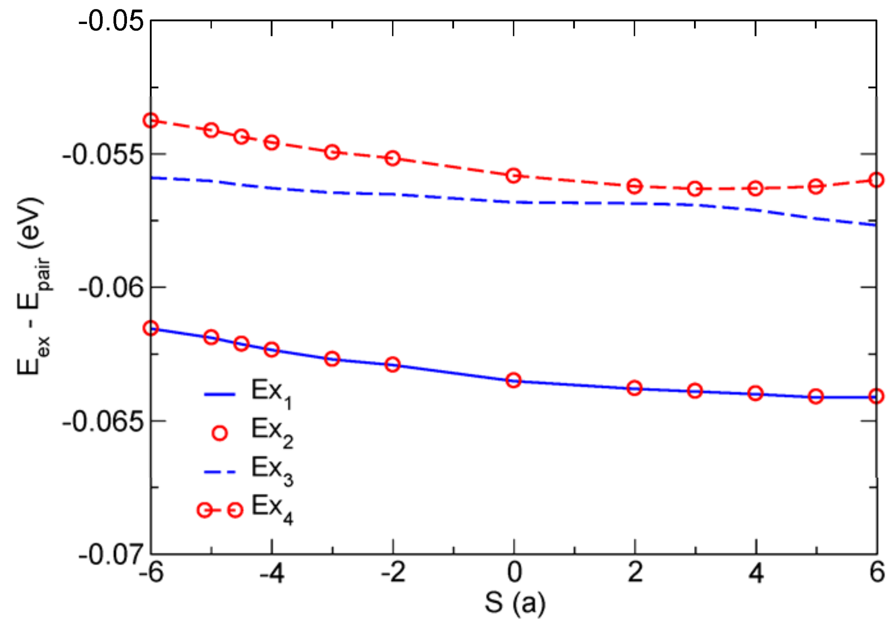
Excitons: biaxial deformation





Exciton energy follows pair ground state

Binding can increase or decrease by bending (charge shifting)



<u>Fine structure: level splittings</u>

Ex_1 and Ex_2 are dark

Ex_3 and Ex_4…exchange split bright states

Ex_3 and Ex_4…asymmetric exchange

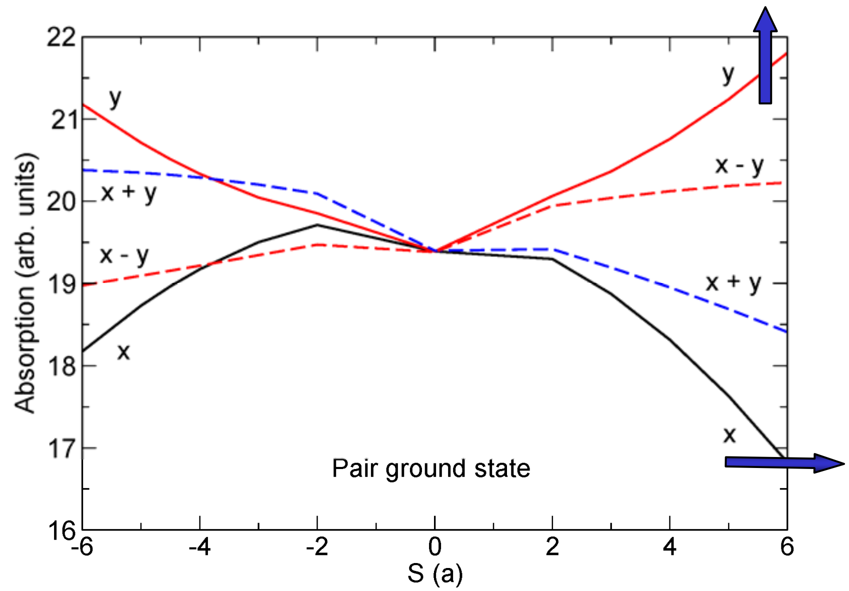
Bend-induced anti-crossing and polarization rotation

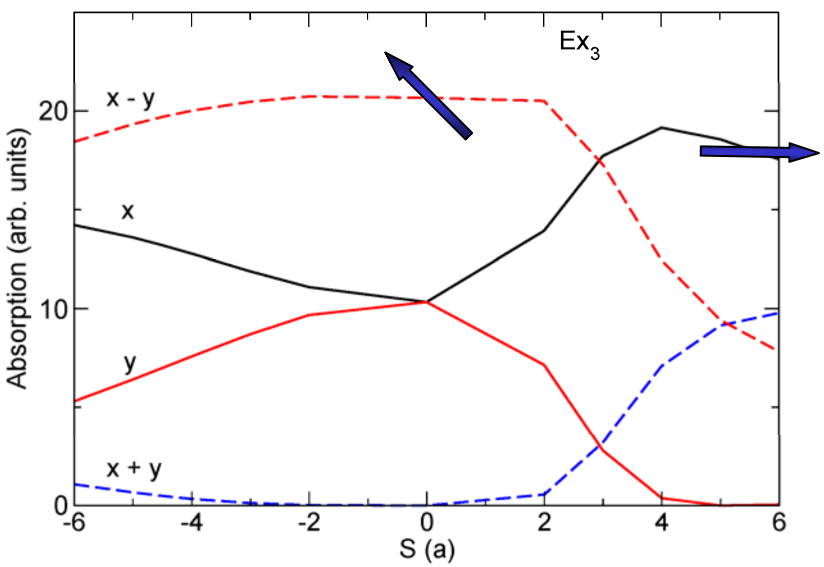
Excitons: biaxial deformation

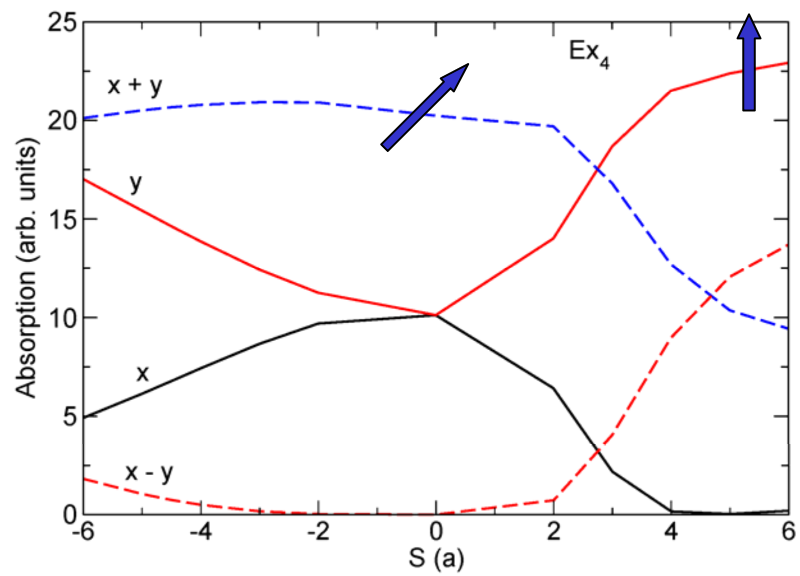
Pair ground state weakly polarized, strain polarizes along y

$Ex_{3(4)}$ polarized along x-y (x+y) in unbent structure

Polarization rotates to x (y) by bending



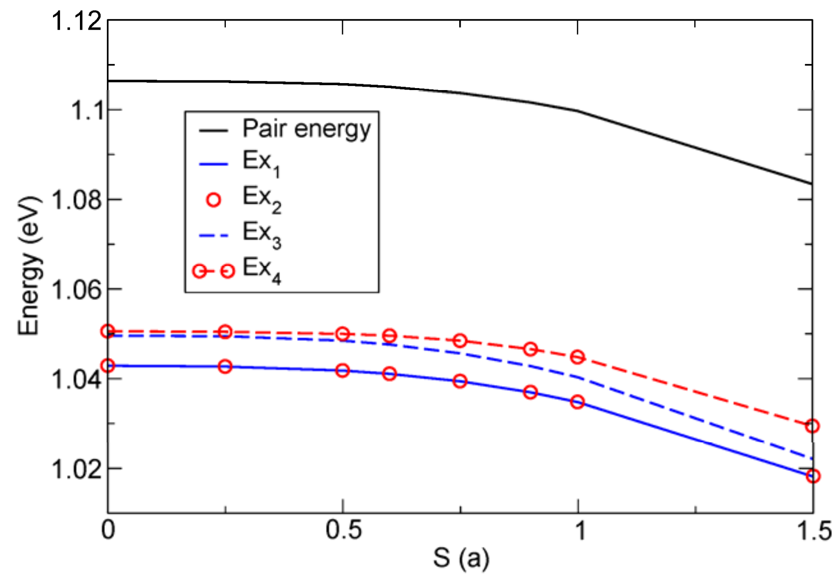




Excitons: shear

Exciton energy follows pair ground state

Binding increases by bending (hole squeezing)



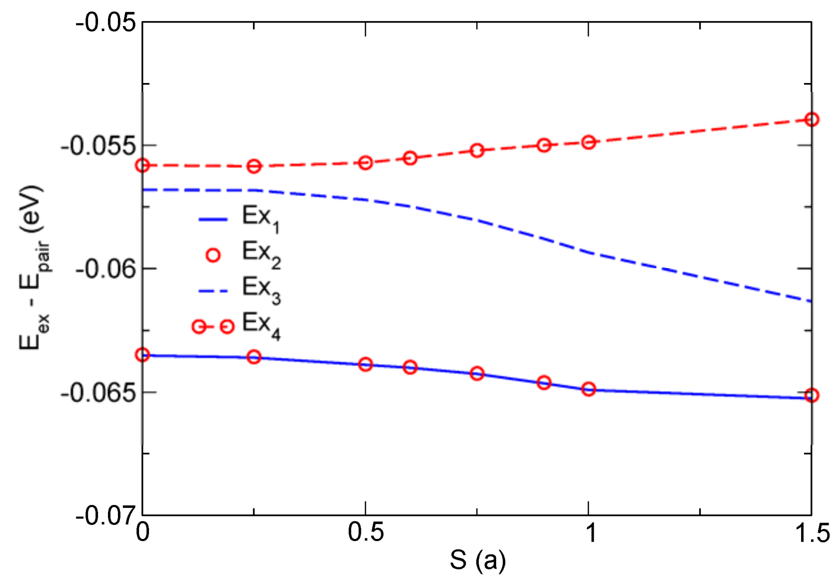
<u>Fine structure: level splittings</u>

Ex_1 and Ex_2 are dark

Ex_3 and Ex_4…exchange split bright states

Ex_3 and Ex_4…asymmetric exchange and strong coupling

Bend-induced anti-crossing and polarization rotation

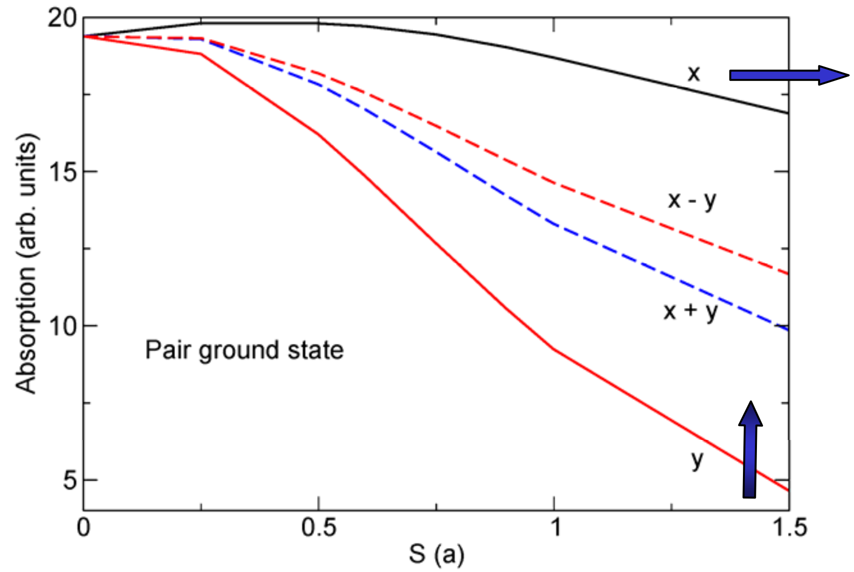


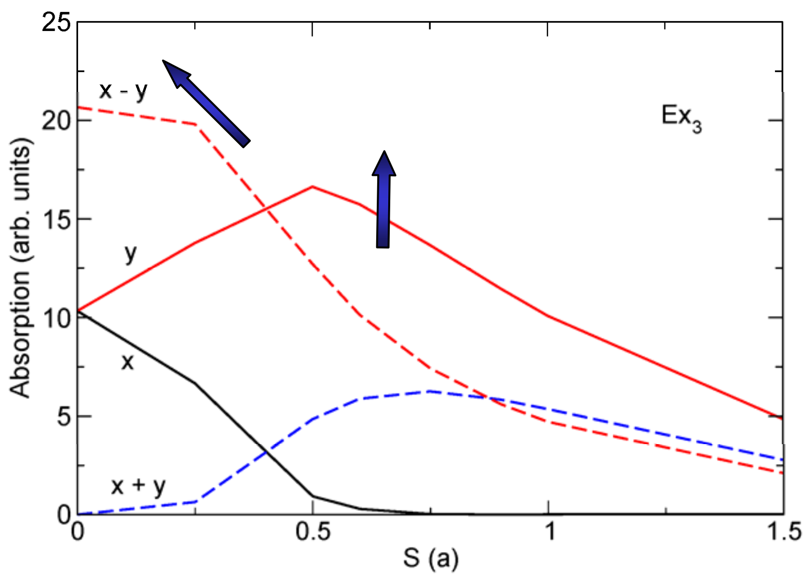
Excitons: shear

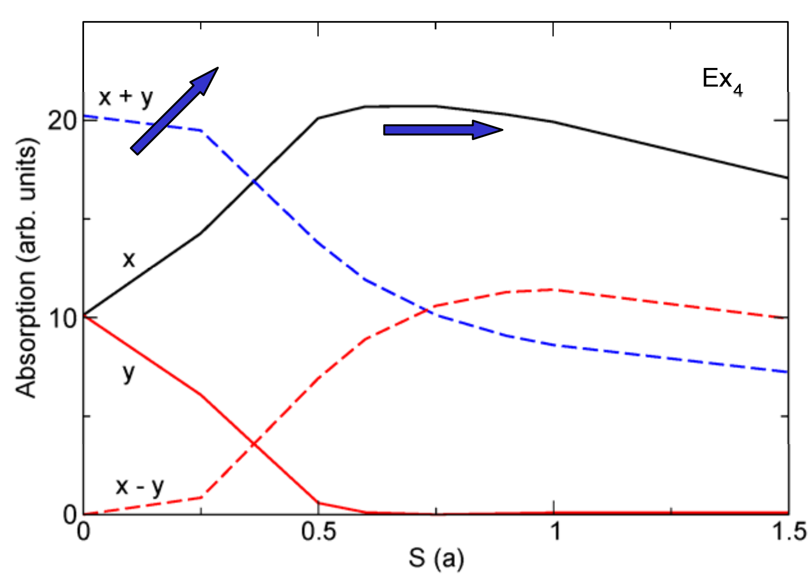
Pair ground state weakly polarized, strain polarizes along x

$Ex_{3(4)}$ polarized along x-y (x+y) in unbent structure

Rotates to y (x) by bending (reverse of biaxial deformation)



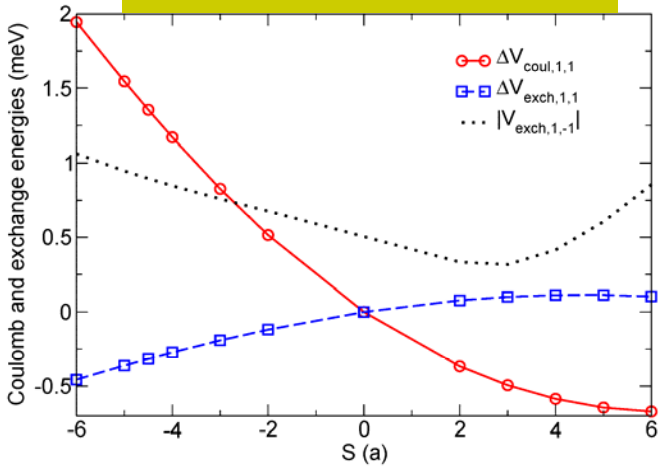




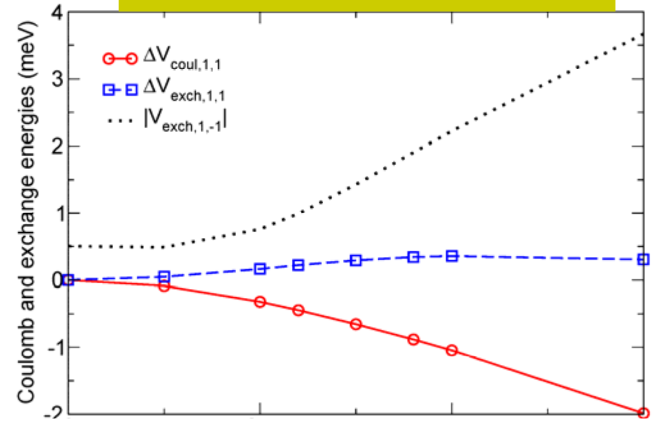
Reengineering excitons: tuning the exchange coupling

Strain-induced tuning of the <u>magnitude</u> of the exchange coupling between S_z= ±1 e/h pair states determines the splitting between bright states

Biaxial deformation



Shear deformation



Strain-induced tuning of the <u>phase</u> of the exchange coupling between S_z= ±1 e/h pair states determines the polarization of bright states