Optical measurements under high pressure in semiconductor nanostructures

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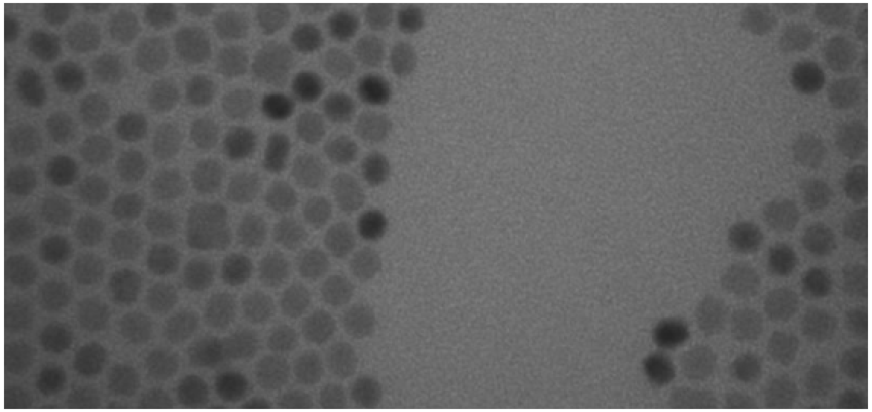
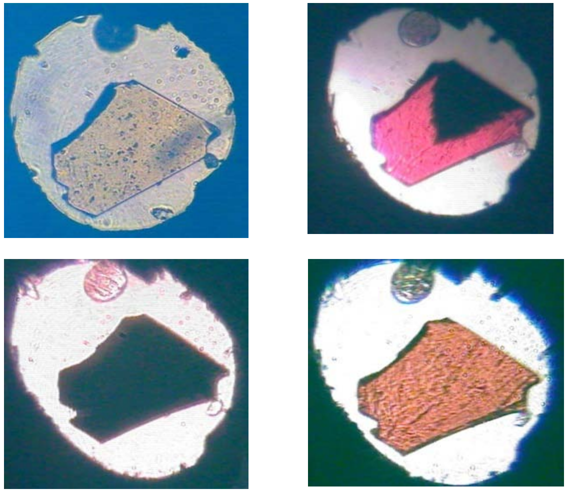


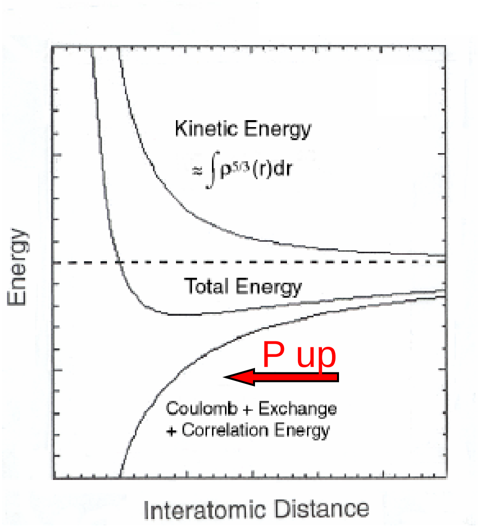


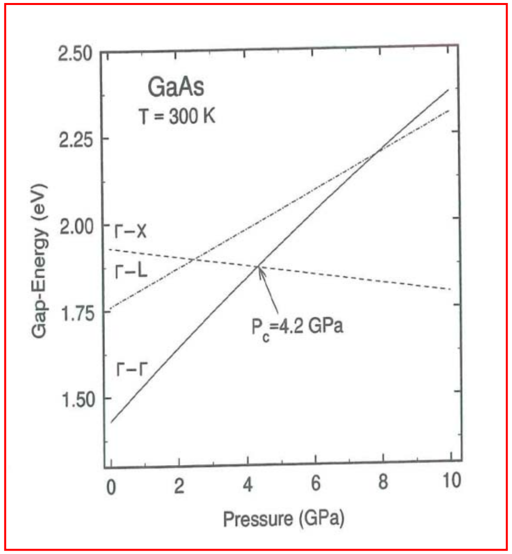
Outline of the talk

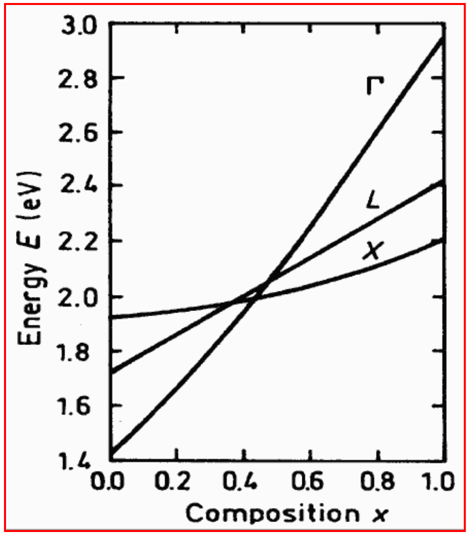
- Why do we study materials under high pressure?
- Experimental: high pressure techniques
- Optical properties of PbSe nanocrystals
- Optical properties InAs quantum wells and quantum wires
- Large metastability range of w- and rs-ZnO nanoparticles
- Conclusions

Why do we study materials under high pressure?

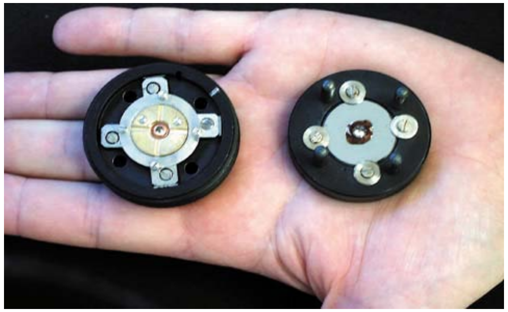
- High pressure is the only available tool to explore the interatomic potentials as a function of the interatomic distance.
- High pressure experiments are the most efficient tests of ab-initio electronic structure calculations.
- High pressure changes the band ordering in semiconductors (equivalence between chemical and mechanical pressure).

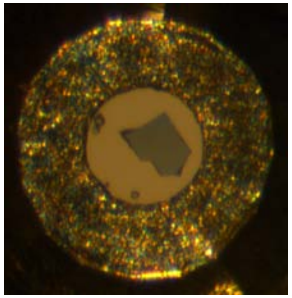


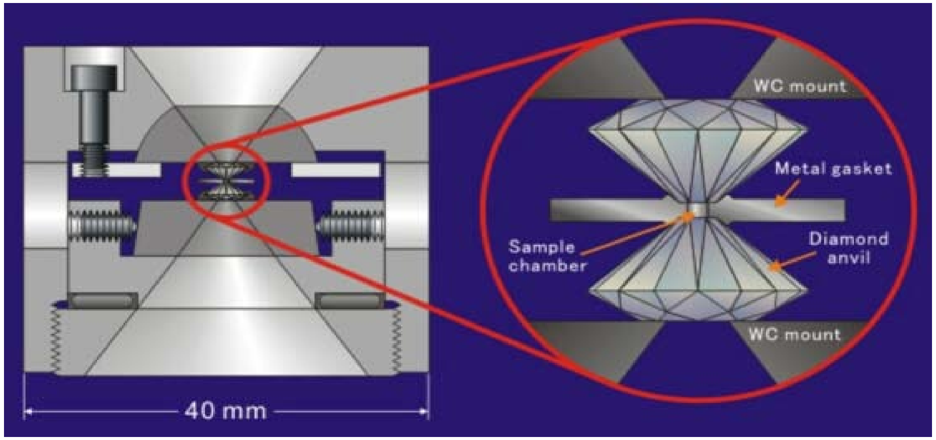


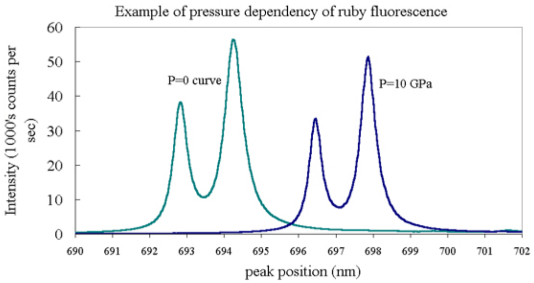


Diamond anvil cells

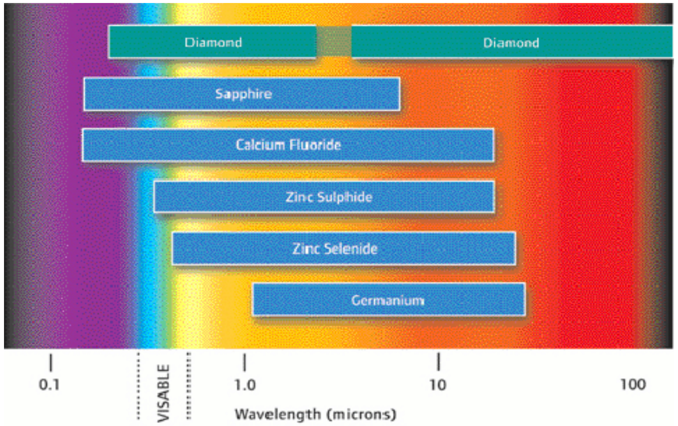




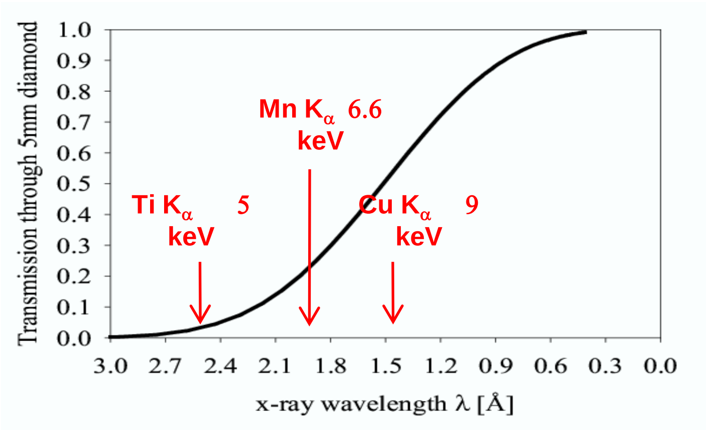




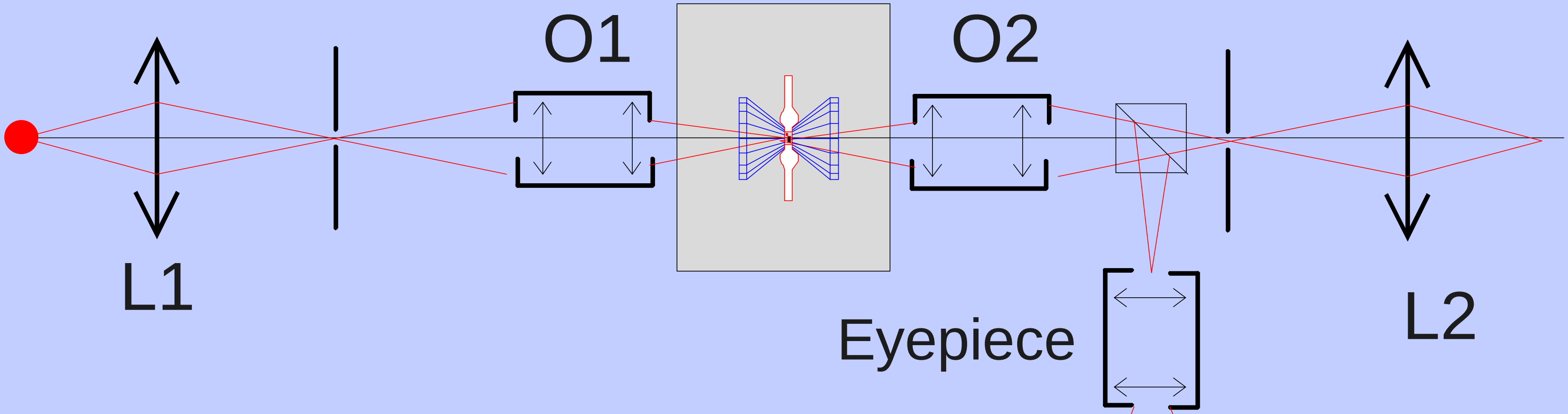
Transparency of diamond UV-VIS-IR

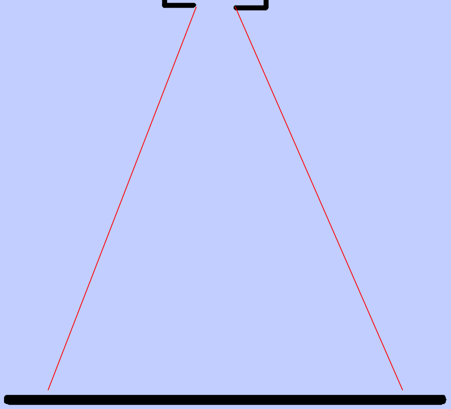


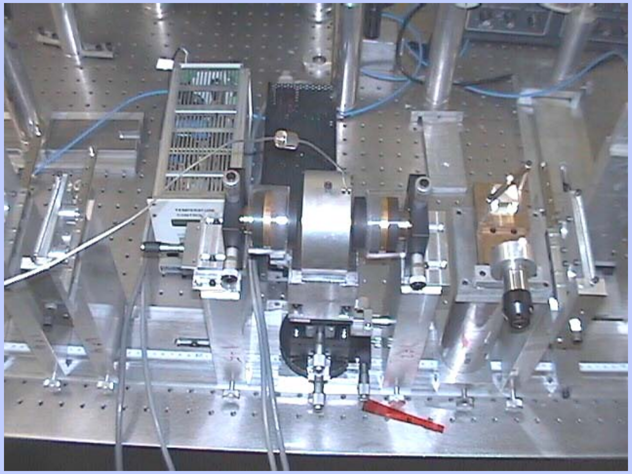
XR transmission of diamond

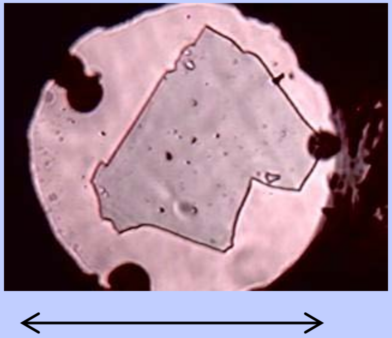


Microscopic optical bench





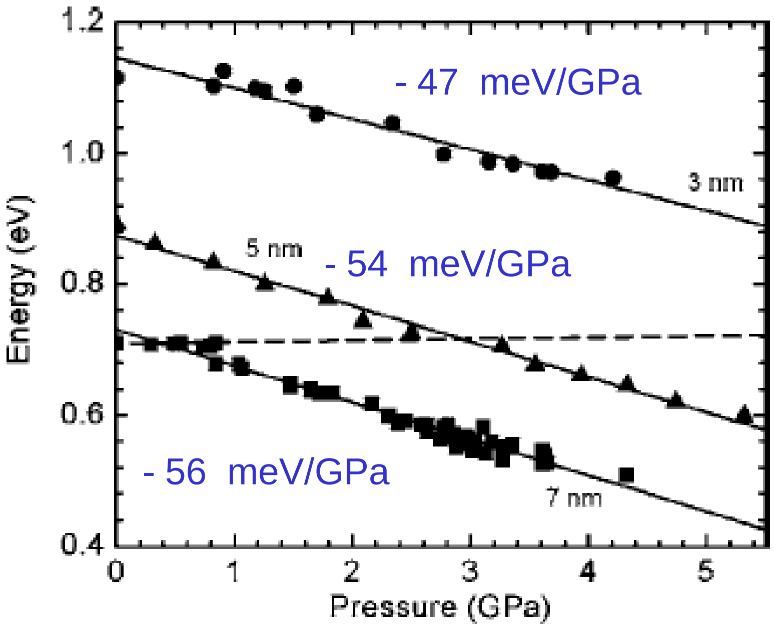




Optical properties of PbSe nanocrystals under high pressure

- Interest for solar cells: multiexciton processes
- Interest for LEDS: wide emission wavelength tuning (0.28–1 eV) and large emission efficiency

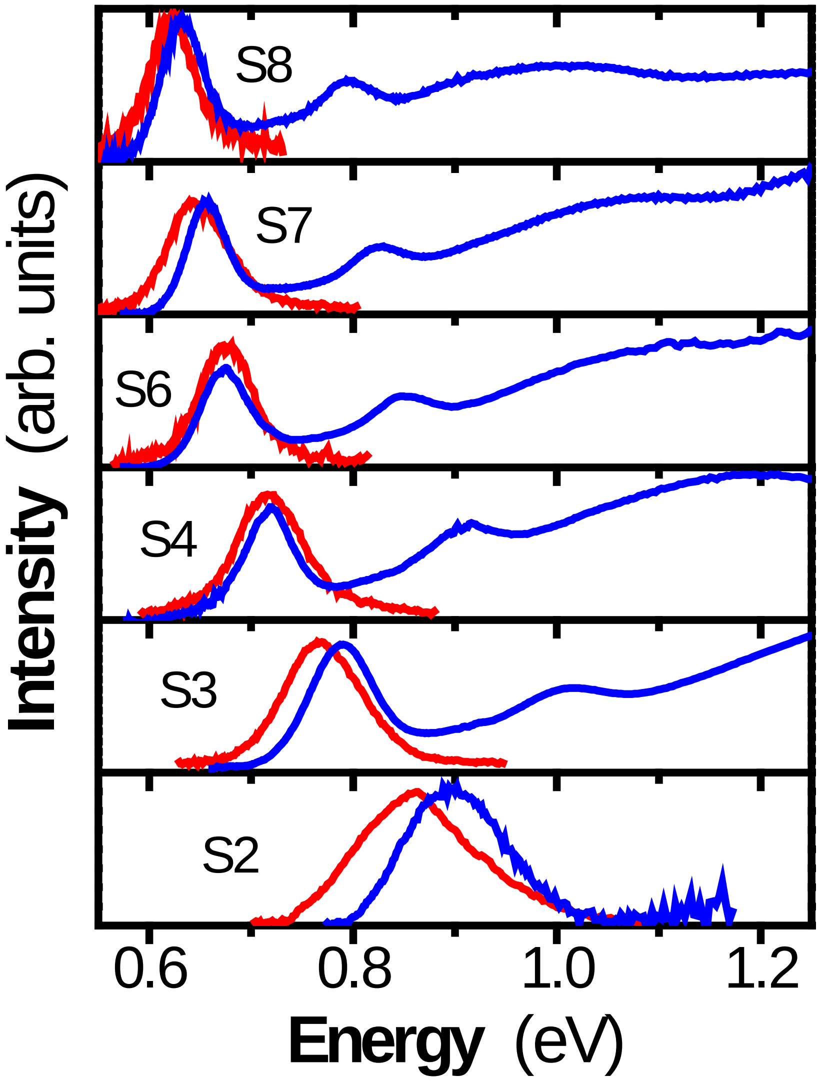
Recent results on PbSe NCs under presssure

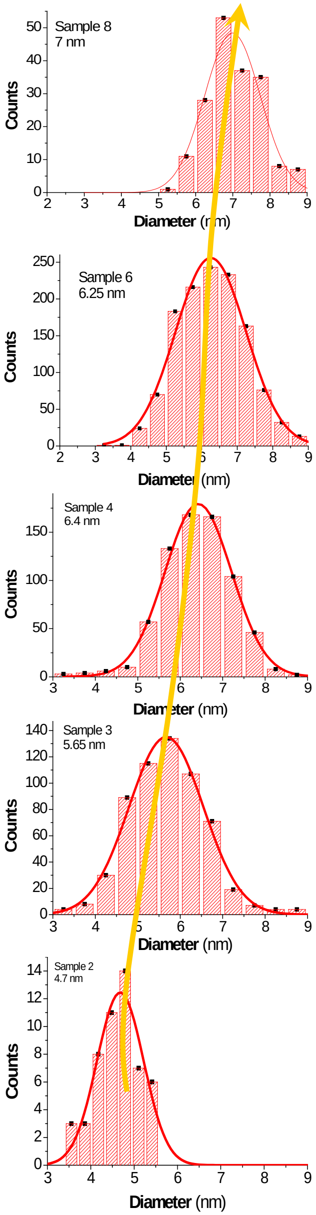


No change of confinement energy under pressure!

Previous results on PbSe gap pressure coefficient: - (85 – 100) meV/GPa

PbSe nanocrystals: size effect





Effective mass model for size confinement in PbSe NCs

- Finite potential barriers for carrier confinement

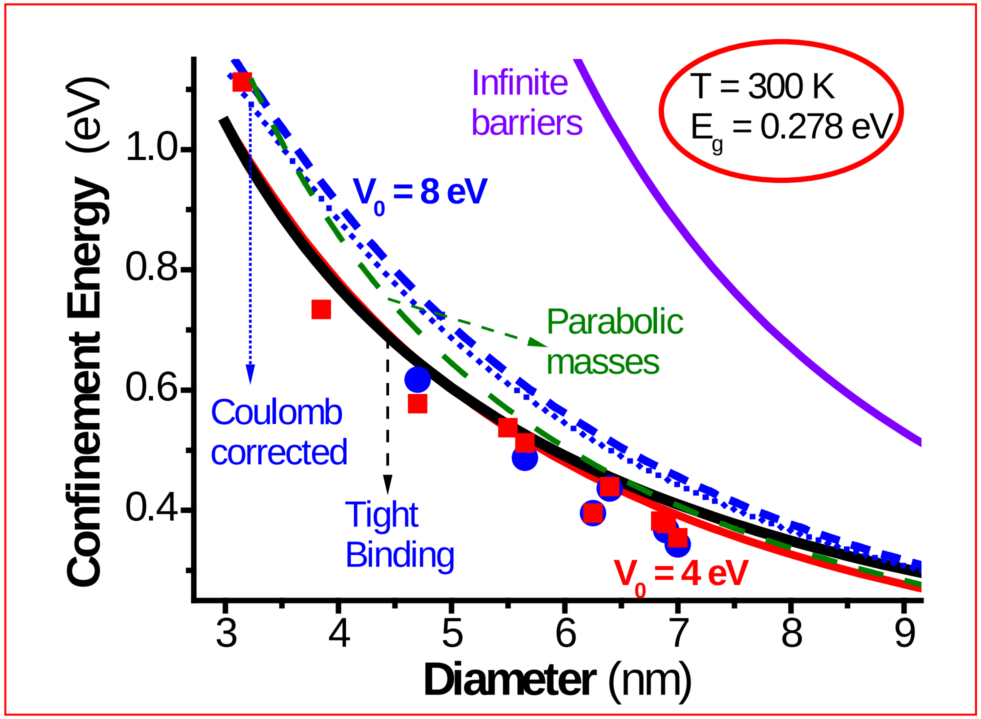
$$x\cot(x) = 1 - \left(\frac{m^*}{m_0}\right) - \sqrt{\left(\frac{m^*}{m_0}\right)\left(\frac{V_0}{\Delta} - x^2\right)},$$

where $x = k_{\text{in}} r_0$. $\quad \frac{1}{\Delta} = \frac{2m^* r_0^2}{\hbar^2} \quad k_{\text{in}}^2 = \frac{2m^* E}{\hbar^2}$ and $k_{\text{out}}^2 = \frac{2m_0|E - V_0|}{\hbar^2}$

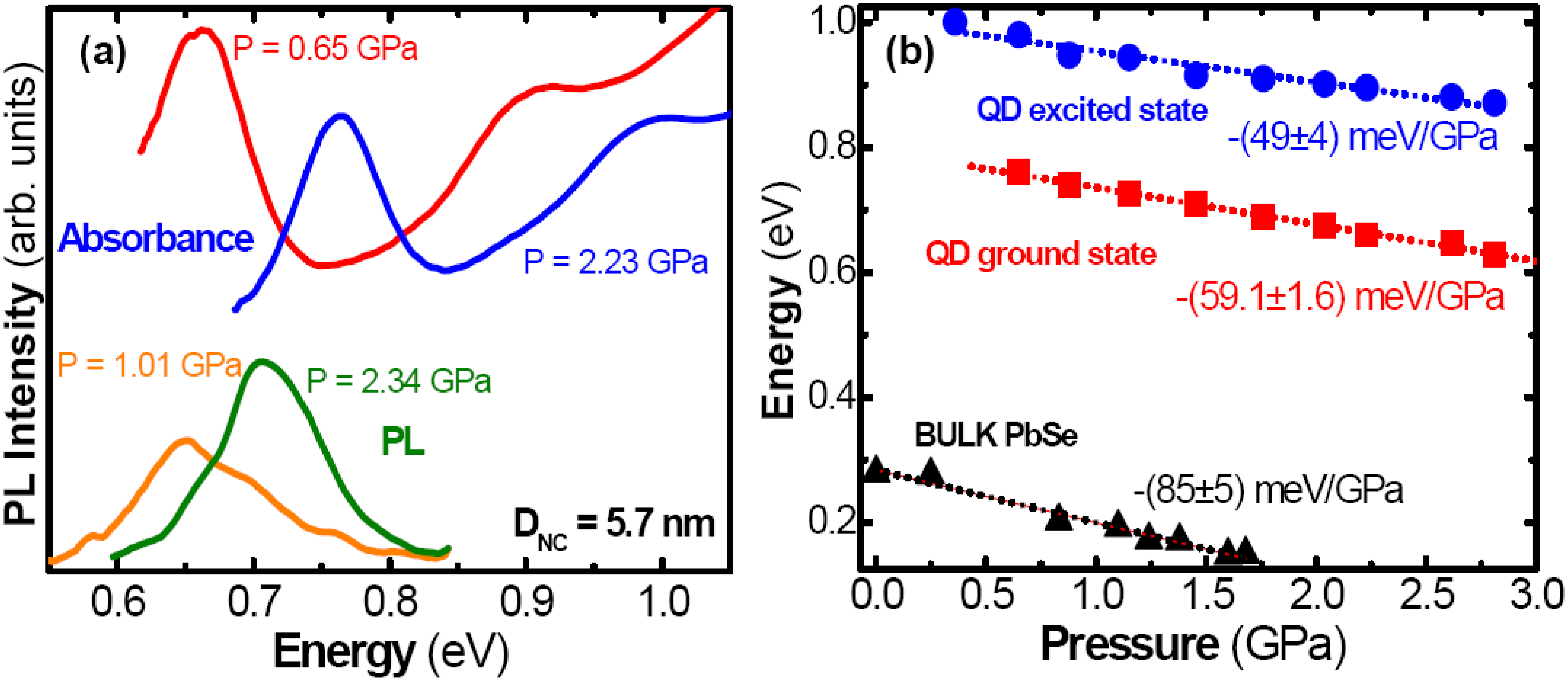
- Non parabolic effective masses

$$m^*_{e,h}(E,X) = \frac{m^*_{e,h}(0,X)}{\sqrt{1 - \frac{m^*_{e,h}(0,X)}{m_0}\frac{E}{E_{np}}}}; \qquad X = T, P$$

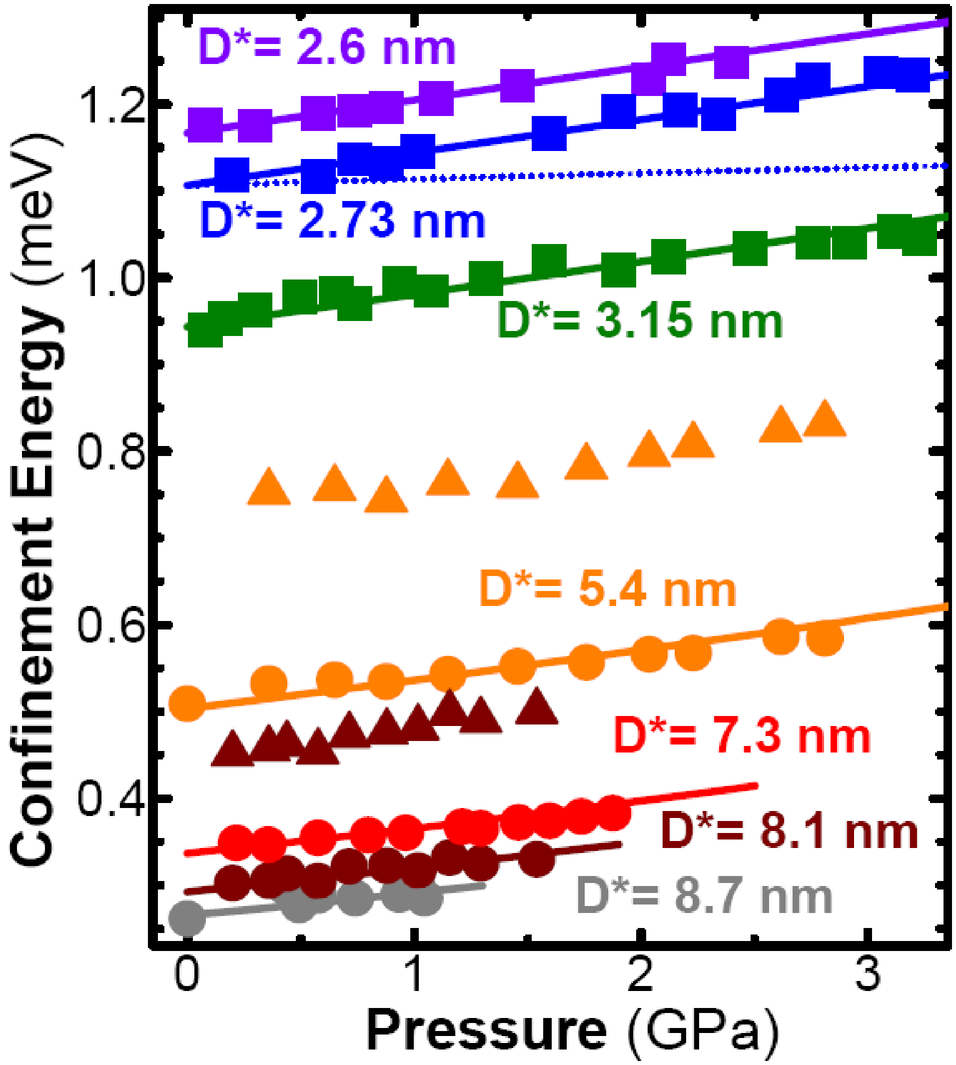
$$E_{np} = \frac{\hbar^2}{8m_0\gamma} = 0.05 \ \ eV; \qquad \gamma = 1.9\times10^{15} \ \ cm^{-2}$$

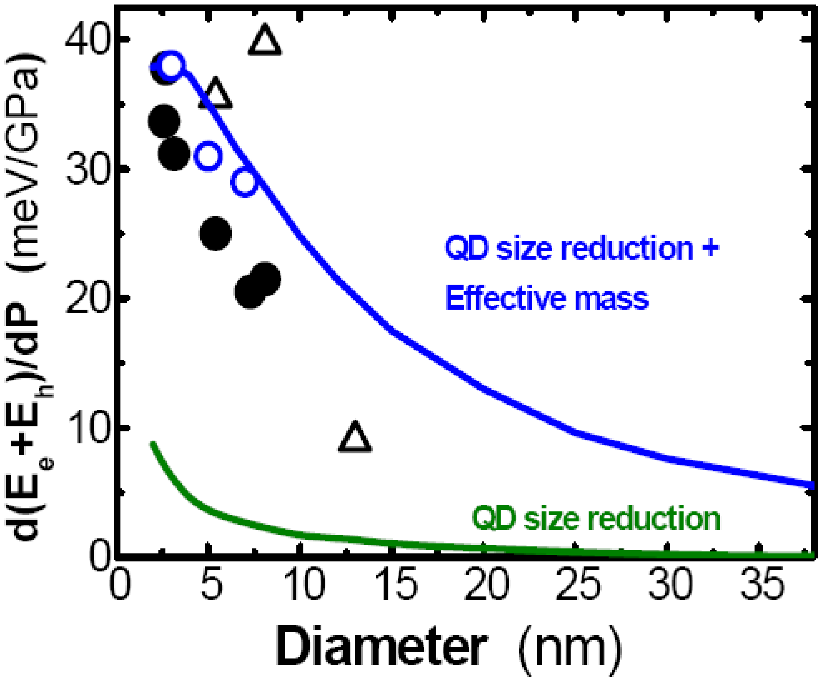


PbSe (bulk and NCs) under high pressure

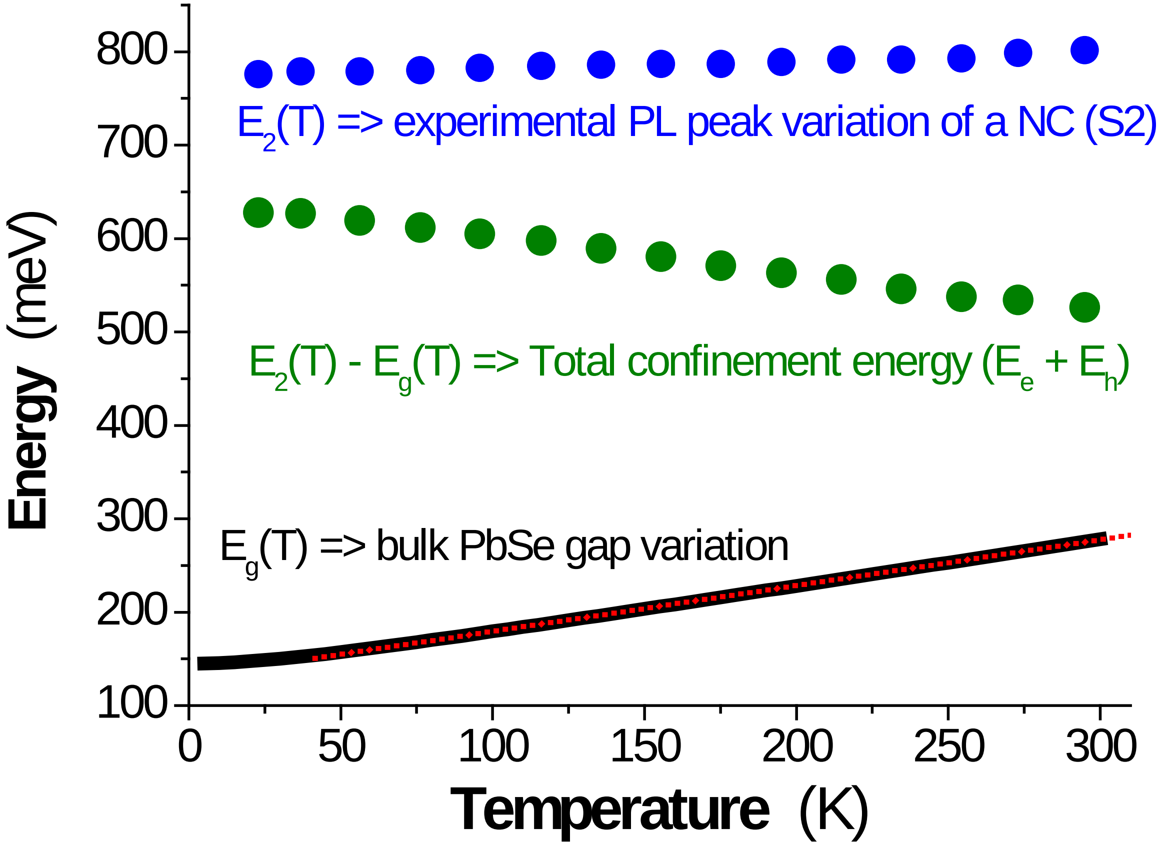


Confinement energy in PbSe NCs under high pressure



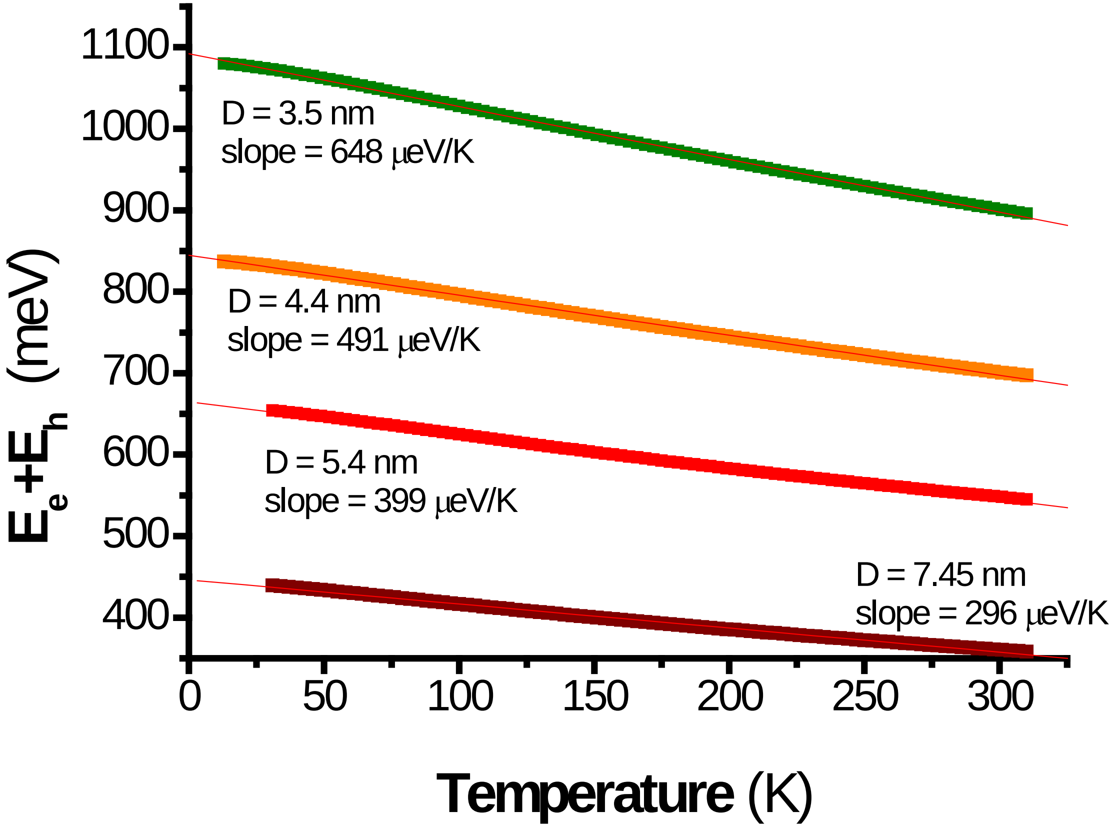


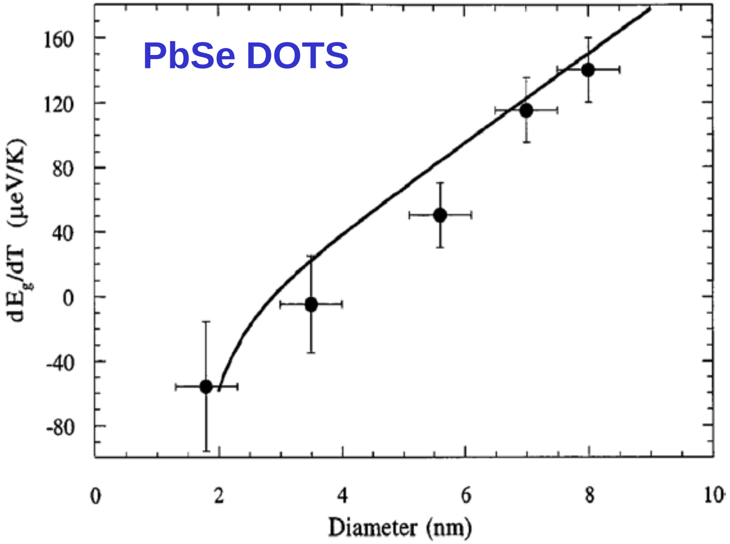
Temperature dependence of electronic transitions in PbSe NCs



Temperature dependence of the confinement energy in PbSe NCs

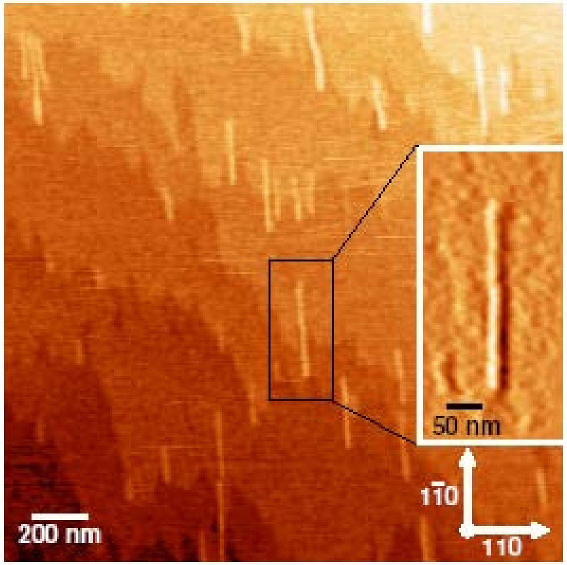
The increase of the effective mass with T makes the total confinement to decrease with higher rates for NCs with smaller diamters.

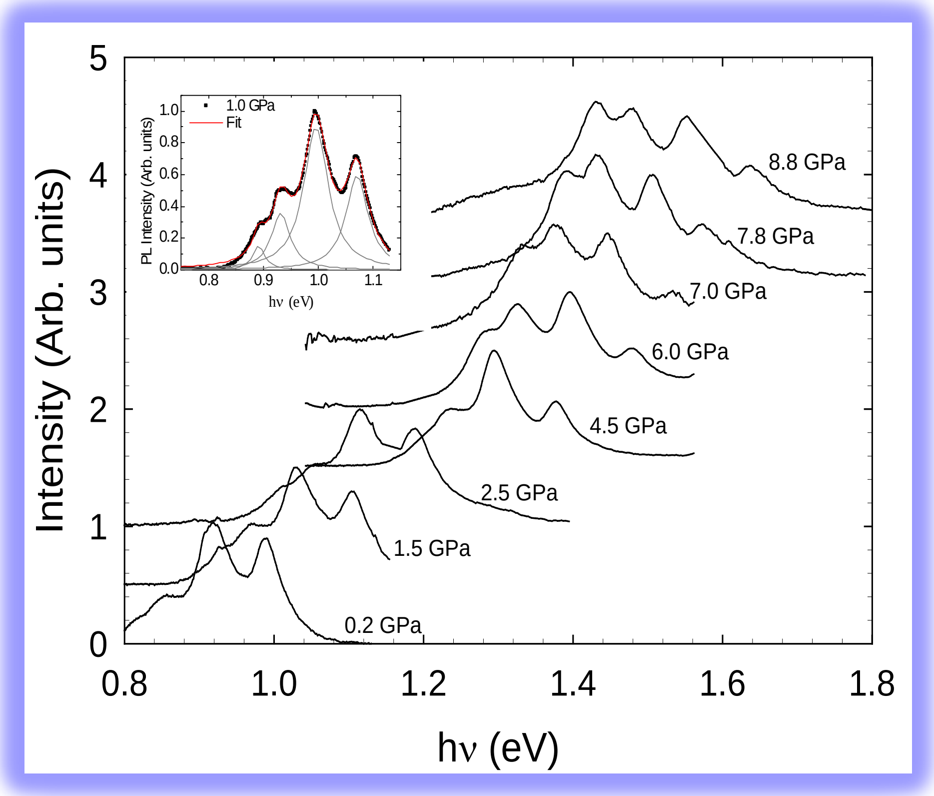




PL in InAs/InP quantum wires under pressure

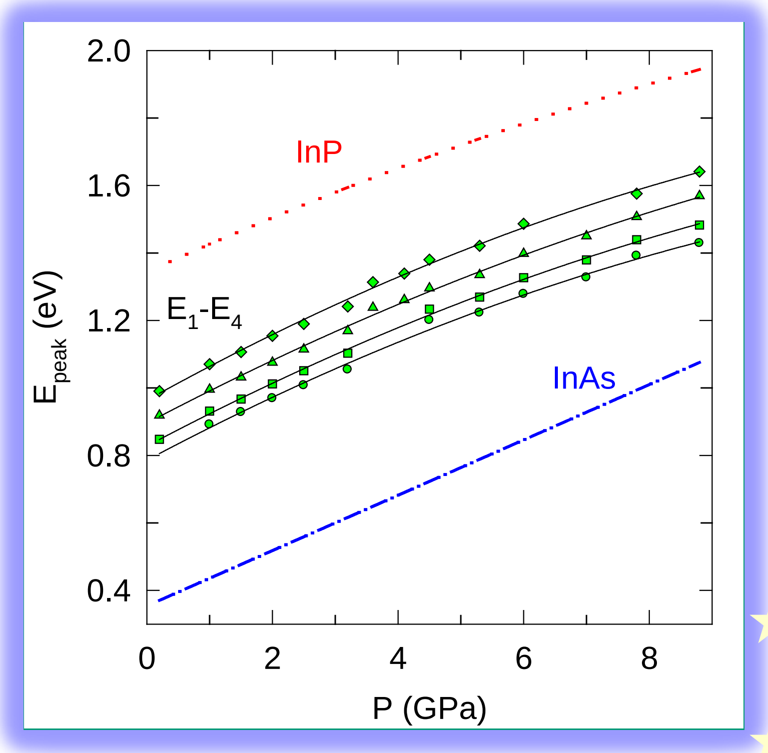
- Dimensions of QWires :average height (2.5 nm), average width (21 nm), and average length (185nm)
- QWires are randomly distributed
- QWires coexist with flat QWell islands of 1-2 ML high





✓ Four PL bands observed. The two bands with higher energy mainly arise from exciton recombination at the QW-like islands

PL in InAs/InP quantum wires under pressure



Peak	E_0 (eV)	a_1 (meV/GPa)	a_2 (meV/GPa^2)
QWr-E_{1A}	0.786	99	-2.9
QWr-E_{2A}	0.828	98	-2.7
QW-E_{3A}	0.896	98	-2.5
QW-E_{4A}	0.964	103	-3.0

- Pressure coefficient InP: 85 meV/GPa
- Pressure coefficient InAs: 100 meV/GPa?

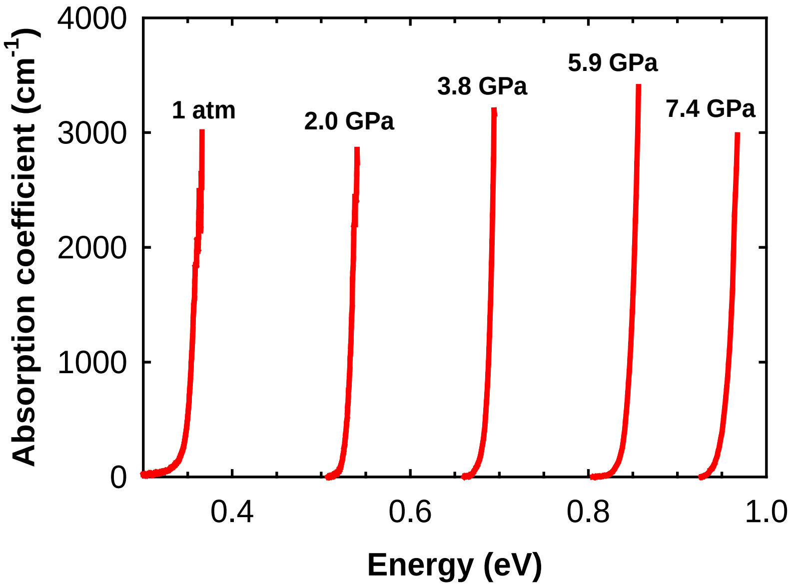
✓ QWrs and QWs pressure coefficients similar to those of InAs?

✓ Slightly larger pressure coefficients for the QW islands than for the QWrs?

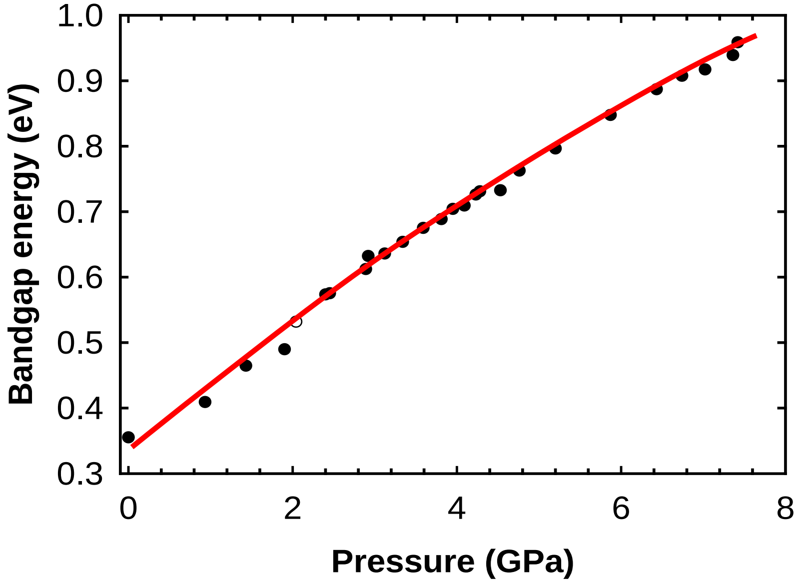
Optical absorption in bulk InAs under pressure

Sample thickness: 14 μm
FIR and MIR: FTIR spectrometer
NIR: dispersive spectrometer

Optical absorption edge of InAs



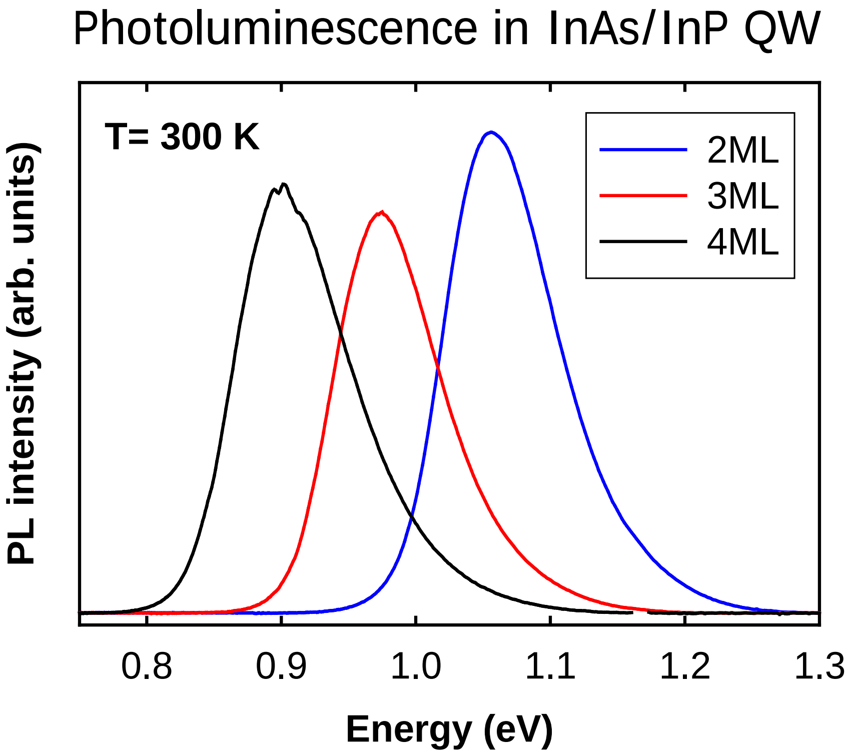
Bandgap energy in InAs

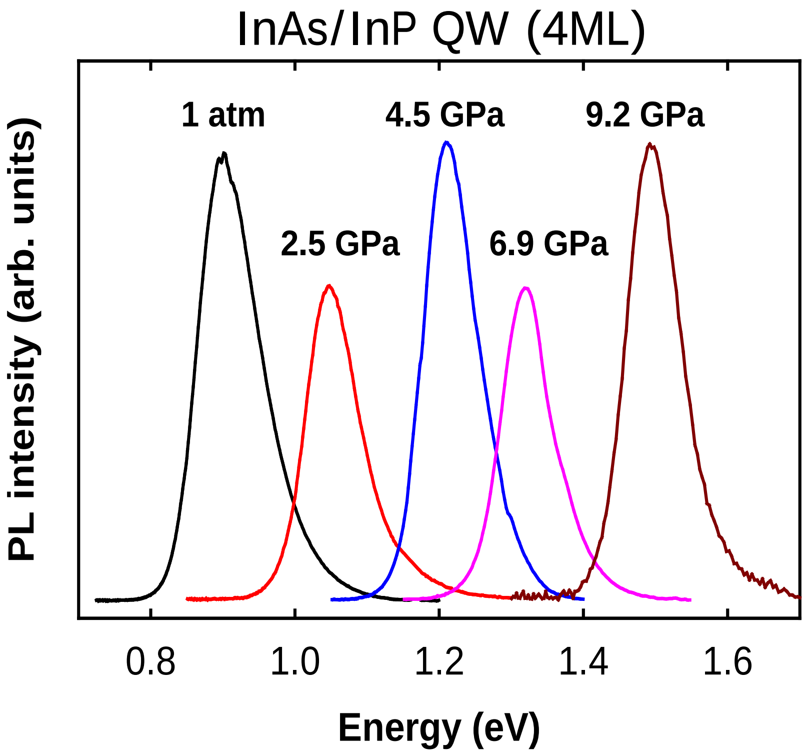


$$E_g = 0.333 + 0.104 \cdot P - 0.003 \cdot P^2$$

InAs direct bandgap pressure coefficient: 104 4 meV/GPa

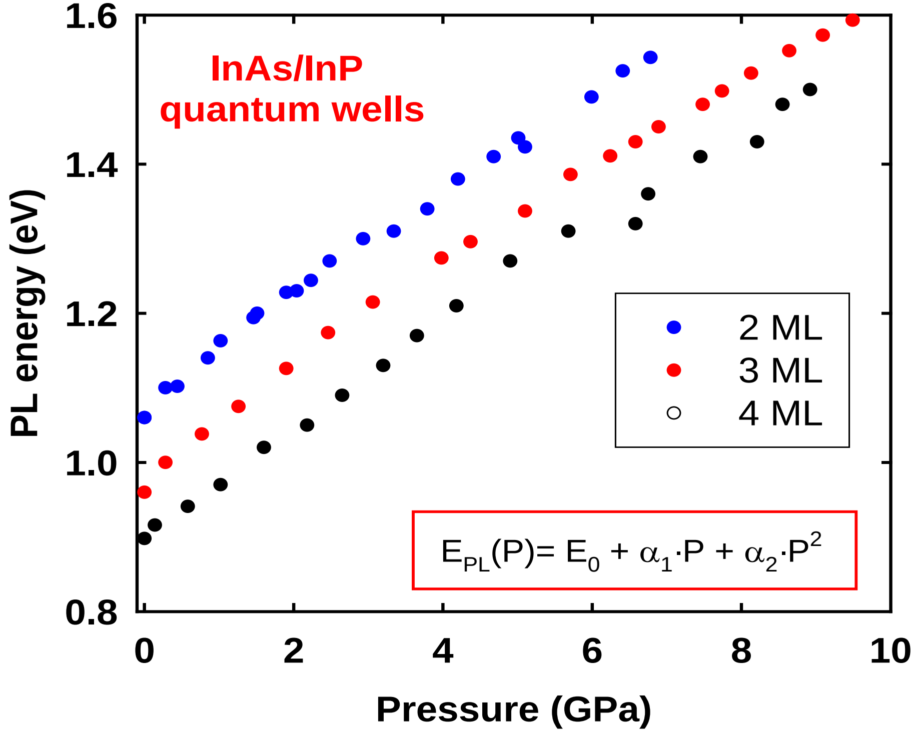
PL in InAs/InP quantum wells under pressure





InAs/InP	2 ML	3 ML	4 ML
E_0 (eV)	1.055	0.975	0.898

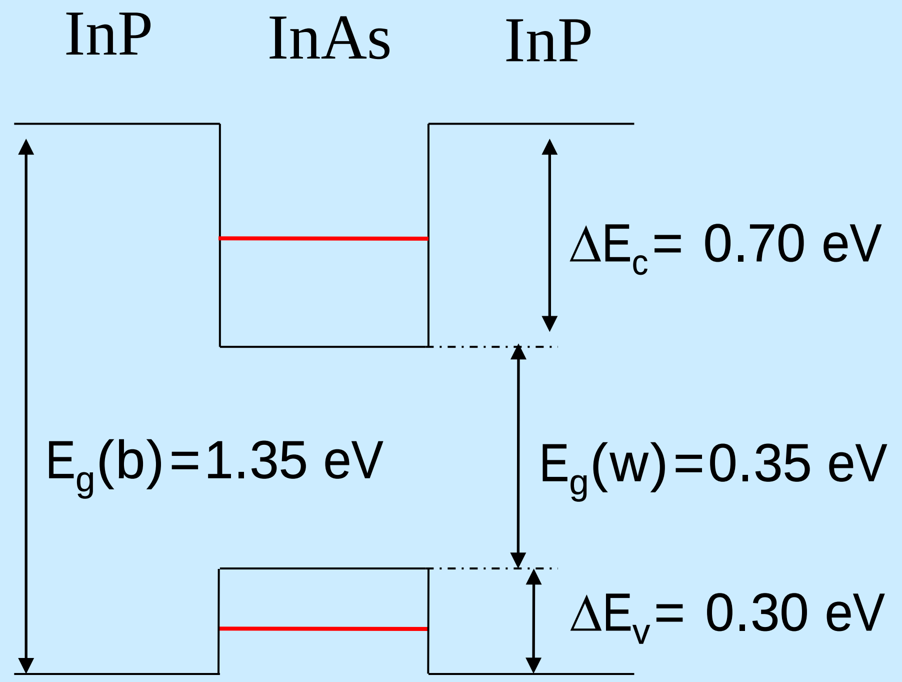
PL in InAs/InP quantum wells under pressure



InAs/InP	2 ML	3 ML	4 ML
E_0 (eV)	1.055	0.975	0.898
α_1 (meV/GPa)	89	83	78

⇒ Similar PC to InP (85)

PL in InAs/InP quantum wells under pressure

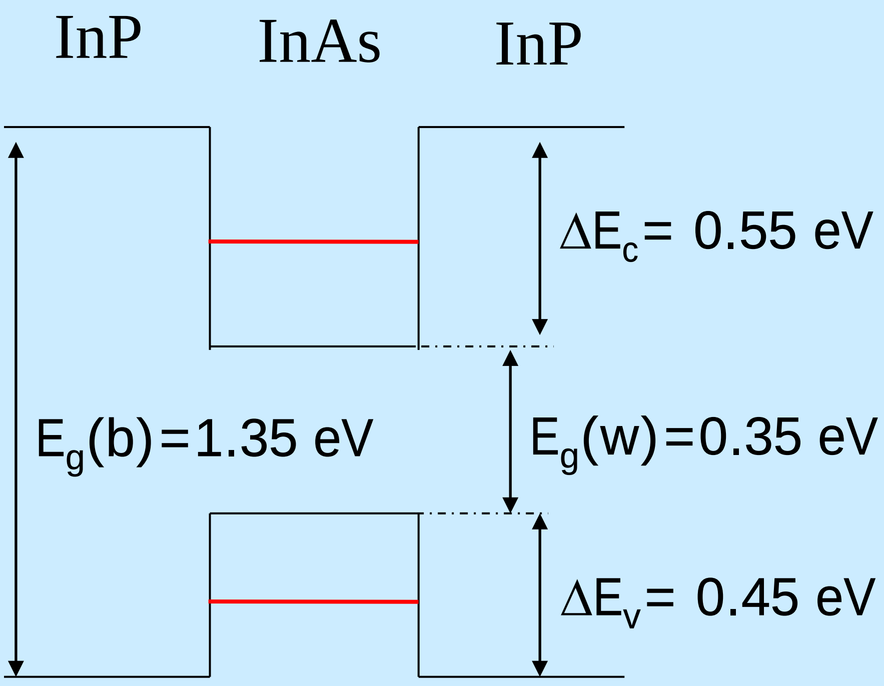


M. Beaudoin et al., Phys. Rev. B 53, 1990 (1996)

InAs/InP	2 ML	3 ML	4 ML
E_0 (eV)	1.055	0.975	0.898

$InAs_xP_{1-x}$ barrier
with x ~ 30%

PL in InAs/InP quantum wells under pressure

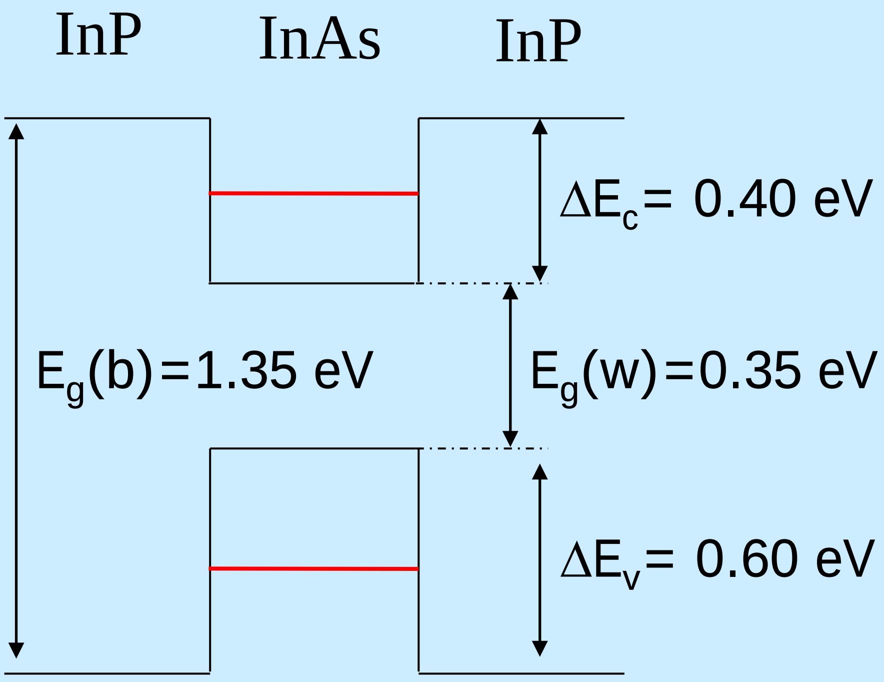


N. Shtinkov et al., Phys. Rev. B 66, 195303 (2002)

InAs/InP	2 ML	3 ML	4 ML
E_0 (eV)	1.055	0.975	0.898

⇨ $InAs_xP_{1-x}$ barrier
with x ~ 15%

PL in InAs/InP quantum wells under pressure



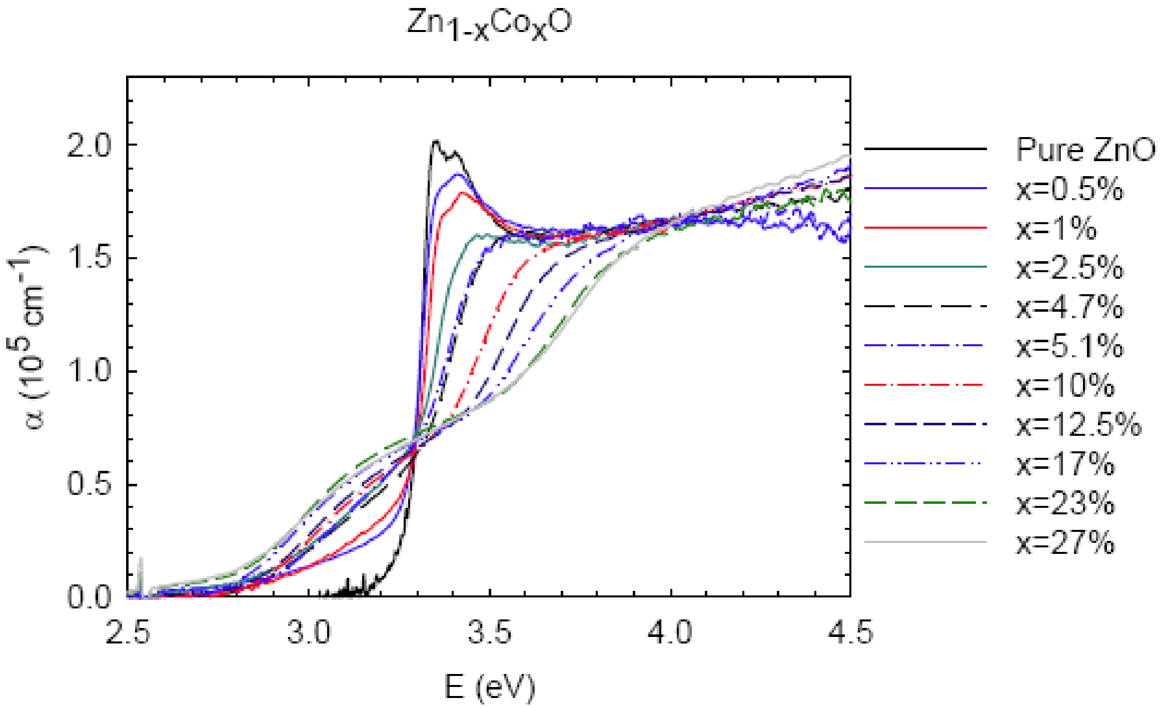
T. Y. Wang et al., J. Appl. Phys. 67, 344 (1990)

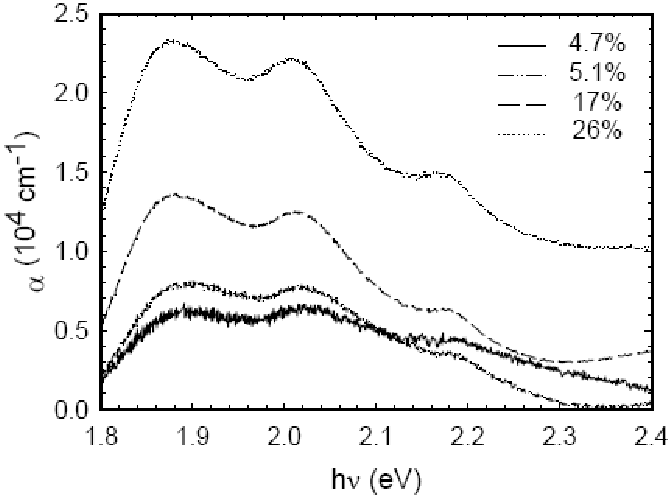
InAs/InP	2 ML	3 ML	4 ML
E_0 (eV)	1.055	0.975	0.898

⇨ OK

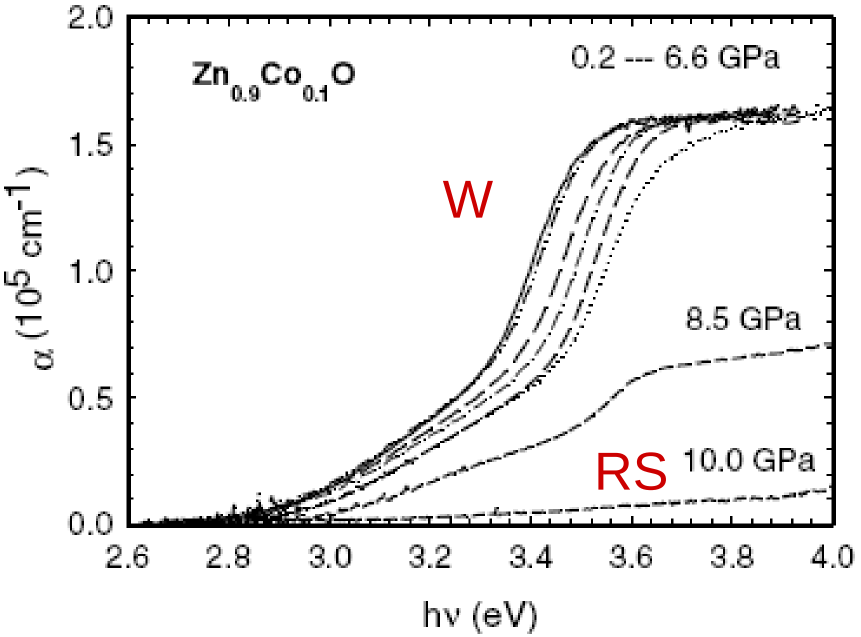
Large metastability range of $Zn_{1-x}Co_xO$ NCs under pressure

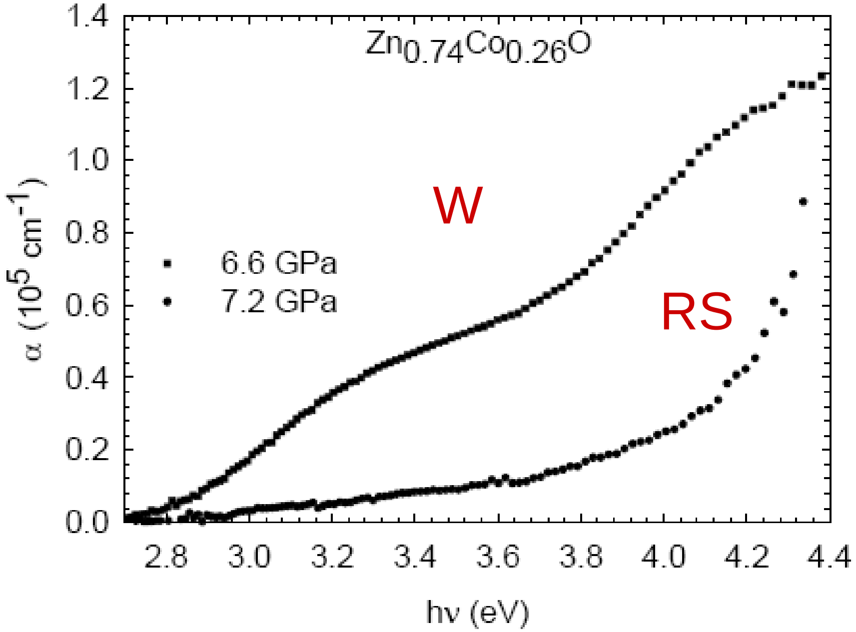
Effect of Co substitution on the optical properties of ZnO (thin films)

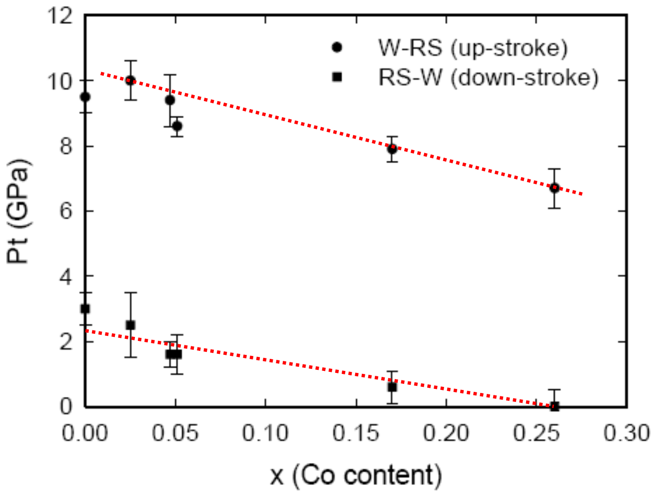




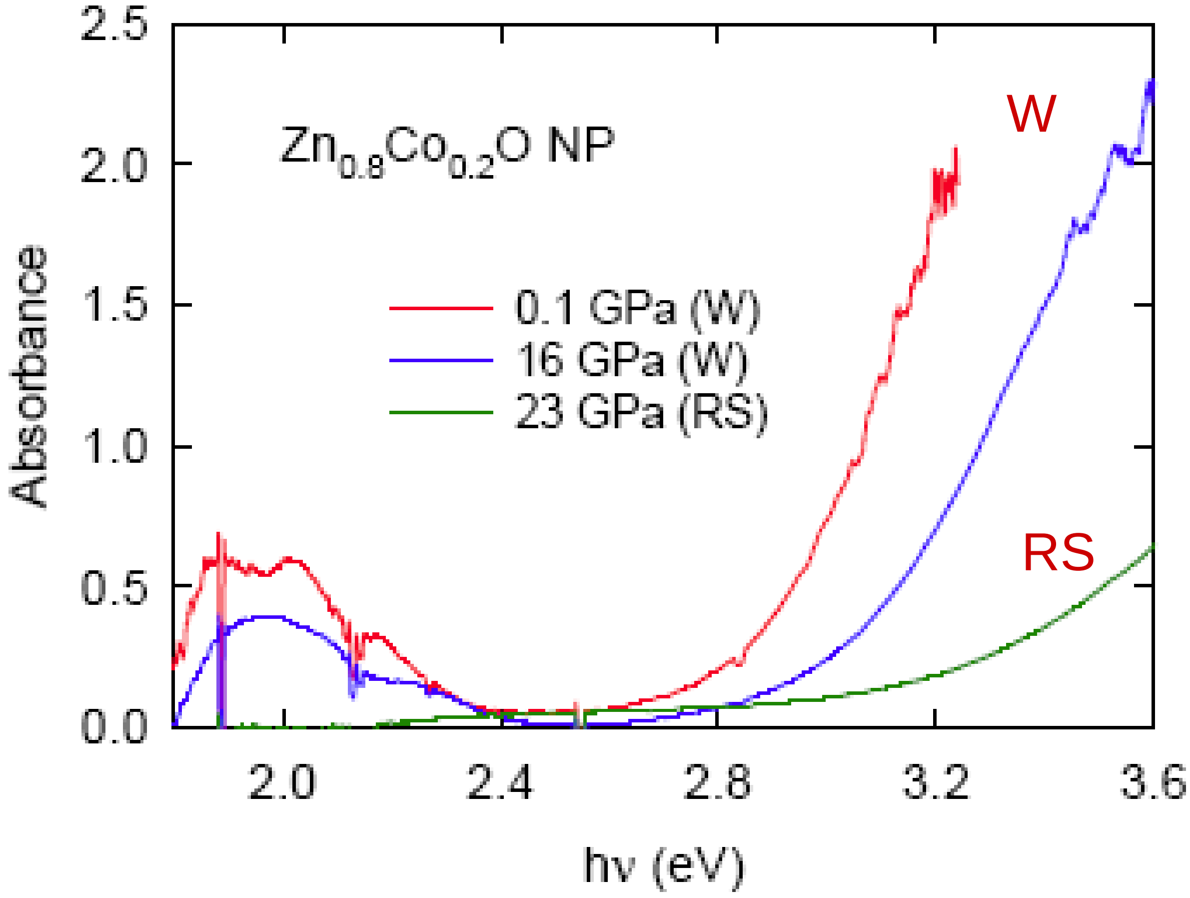
Structural phase transitions in $Zn_{1-x}Co_xO$ thin films under pressure





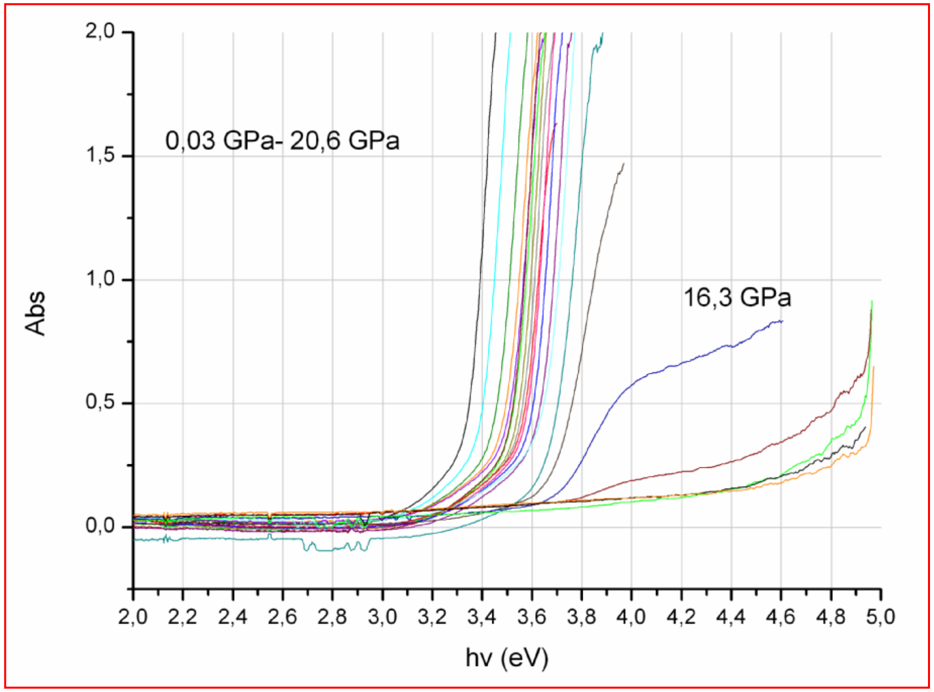


Absorption edge of $Zn_{1-x}Co_xO$ NCs under pressure

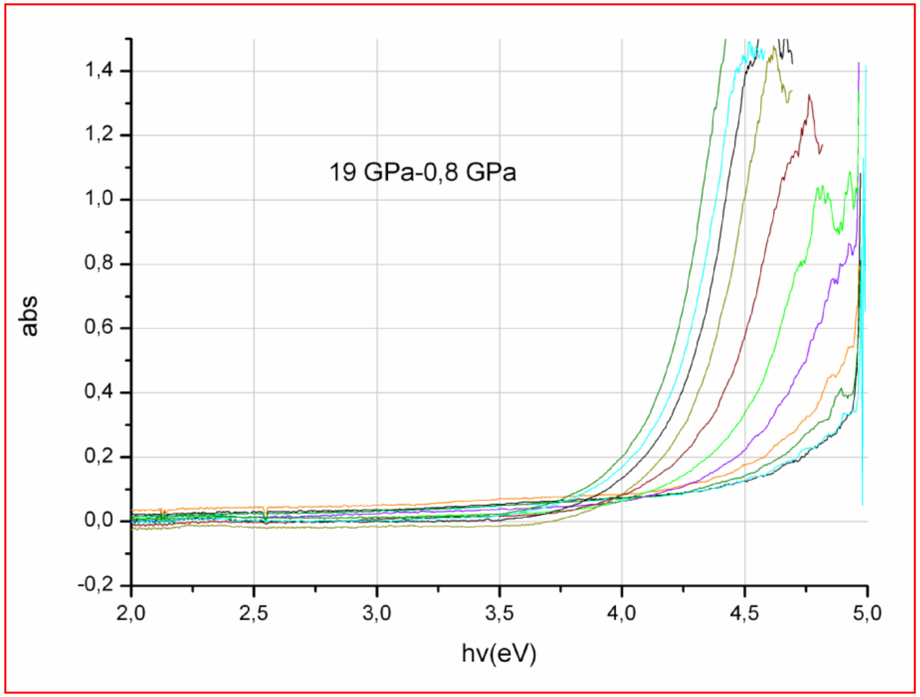


Absorption edge of $Zn_{1-x}Co_xO$ NCs under pressure (x=0.01)

Up-stroke

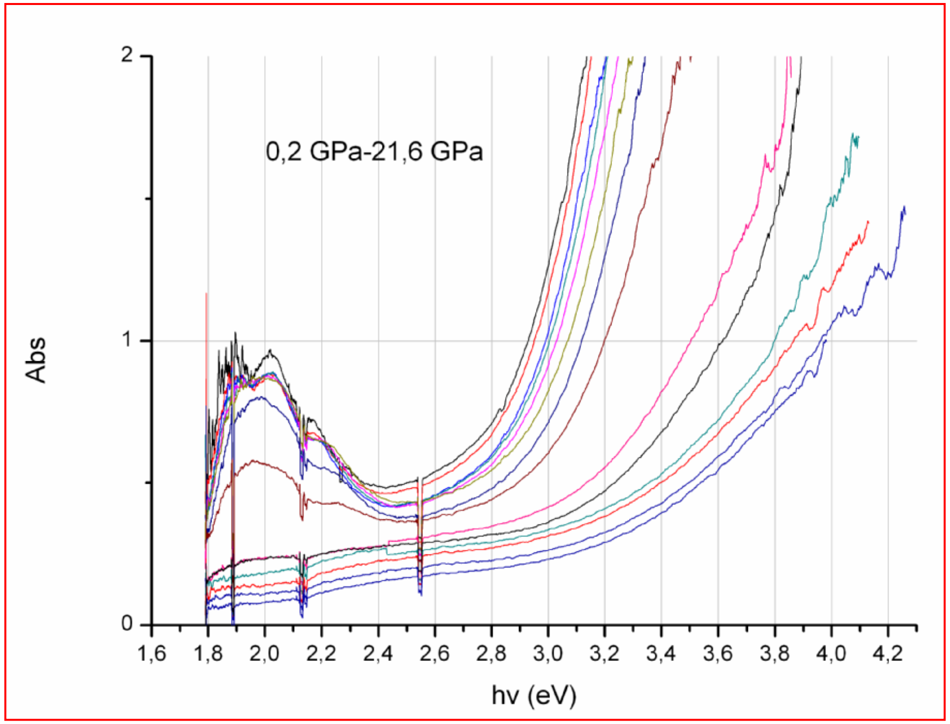


Down-stroke

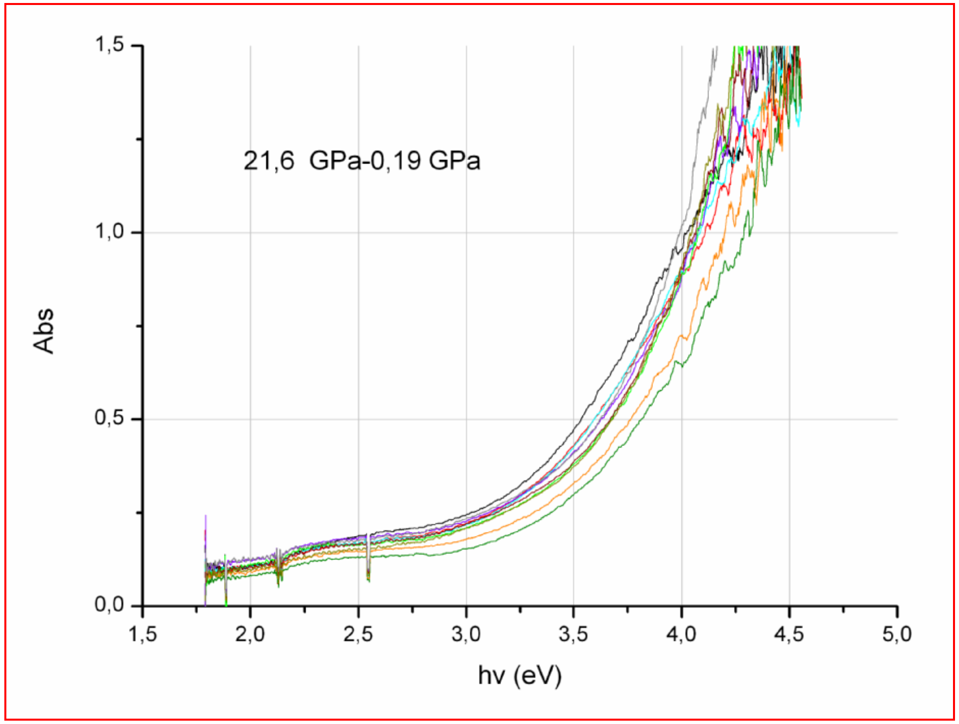


Absorption edge of $Zn_{1-x}Co_xO$ NCs under pressure (x=0.20)

Up-stroke



Down-stroke



Conclusions

1) Optical absorption and photoluminescence experiments under pressure can be an useful tool to investigate the electronic structure of semiconductor nanostructures.

2) In some cases the interpretation of the results requires sophisticated theoretical methods beyond simple effective mass models.

3) High pressure is also an interesting tool in the preparation of new meta-stable nanostructures.

4) To improve the power of HP methods in nanoscience, by increasing the spatial resolution, new diamond anvil cells can be designed allowing for the use of shorter working distance objectives.

Acknowledgements

PbSe NCs

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InAs QWrs and QWs

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ZnCoO NCs

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