Electronic and optical properties of quantum dots

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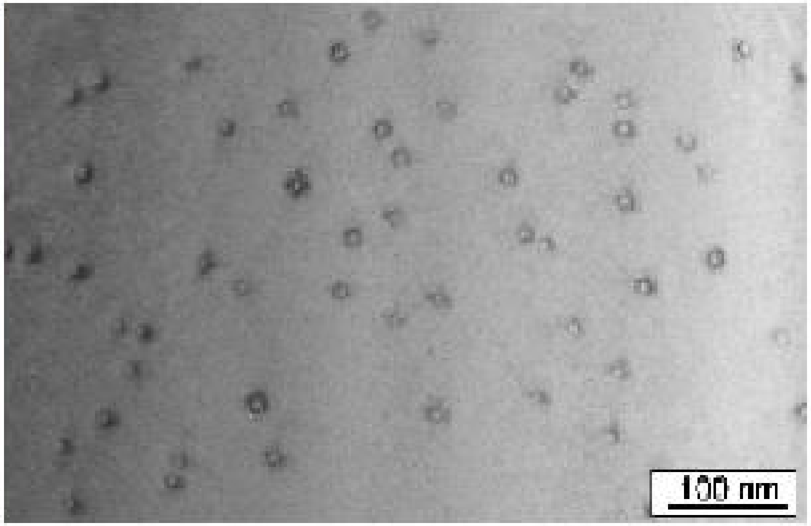
Outline of lectures

- Basics of quantum dot
- Structural properties
- Ensemble QD properties
- Theoretical methods and predictions
  - Envelope function approach
  - **k.p** method
  - Pseudopotential method
- The experimental reality
  - Single QD tunneling spectroscopy
  - Single QD optical properties
  - Single QD tunneling current induced optical properties

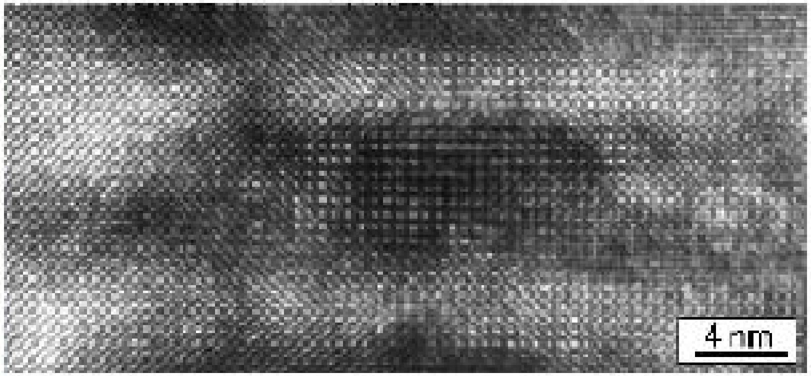
Optical and electronic properties of self-assembled $In_{0.50}Ga_{0.50}As$ QDs

- Exhibit shell structure typical of atoms
  - Charging energy directly reflects the small overlap between the *s*– and *p*–state as compared to two *s*– or two *p*–states
  - Show the influence of the electronic shell structure on the Coulomb repulsion
- However in optical spectra these phenomena are masked due to inhomogeneous broadening

Ensemble QDs:



TEM image planar view, 002 zone axis

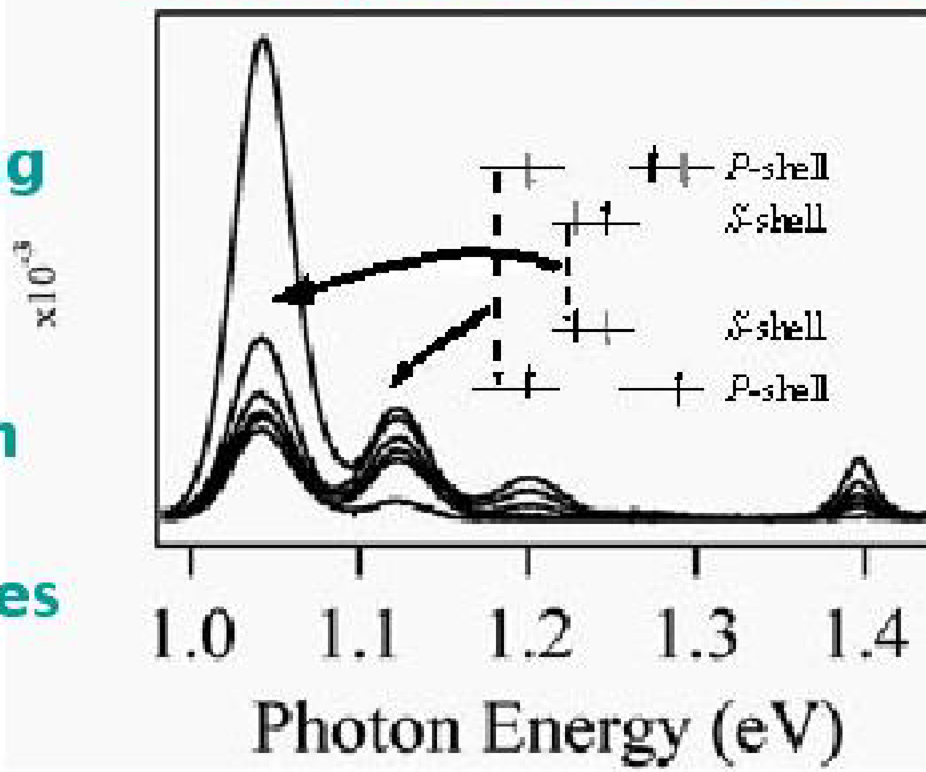


TEM image cross sectional view, 110 zone axis

QD ensemble properties: Photoluminescence

- Broad QD spectra, at least 30 meV broad
- Power dependence, evidence of state filling
- Ground state exciton energy
- With higher excitation power emission from excited excitonic states
- Intra-level spacing

Illumination by Ar laser, 488nm line, sample temperature 30K



QD ensemble characteristics

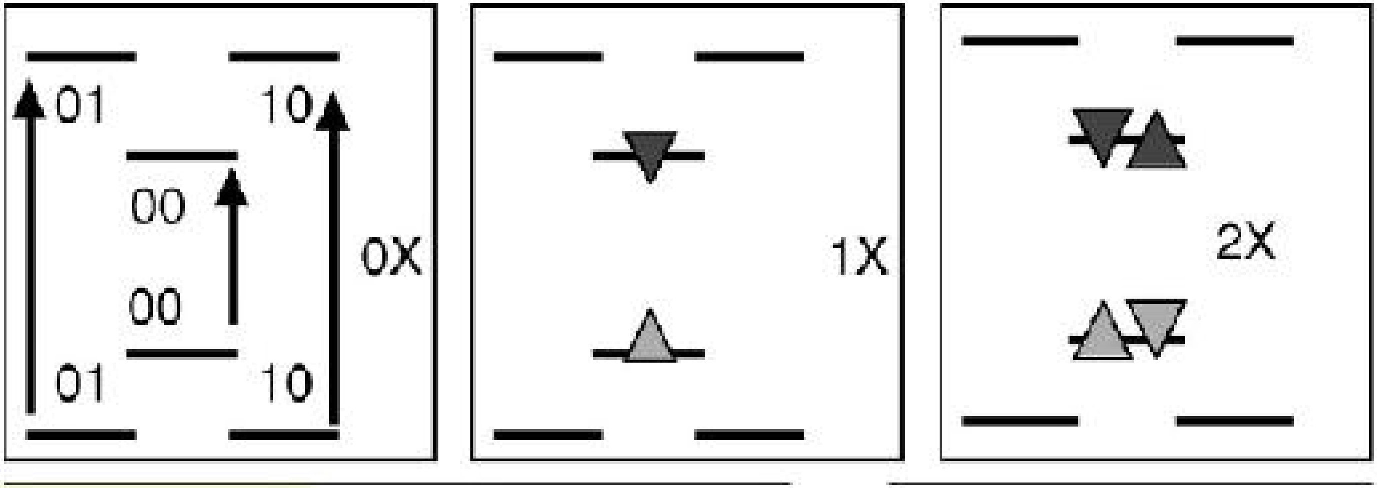
A distribution of QD size and shape.

Usually 10% variation of size and 1% variation of alloy composition

Broadening of spectral features of at least 30 meV

Phenomena such as correlation effects are masked

Multi-particle interactions



Exciton **Bi-exciton**

Single dot spectroscopies

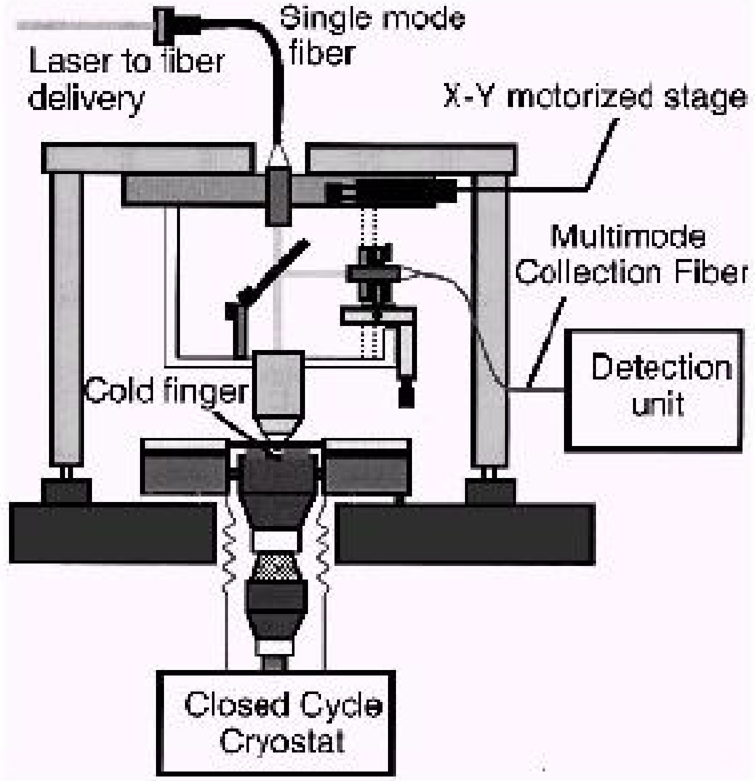
- Isolate signal from a single QD
- Measure photoluminescence
- Inspect binding energy shifts of spectral features with increasing electron-hole pair formation

Scanning probe microscopies

- Micro photoluminescence
  - low cost, large depth of focus
  - sub-micron spatial resolution
- Scanning near optical microscopy
  - spatial resolution 100nm
- Scanning tunneling microscopy
  - Atomic resolution
- Scanning tunneling luminescence
  - controlled injection of carriers
  - spatial resolution limited only by diffusion and capture of carriers

Micro–photoluminescence

- In-house built set up
- Sub-micron spatial resolution
- Large depth of focus
- Large image scan area 25×25mm^2



M. De Vittorio, A. Melcarne, R. Rinaldi, and R. Cingolani, Rev. Sci. Instrum.72, 2610 (2001)

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Effects of few-particle interactions on the atomic-like levels of a single strain-induced quantum dot

- Seek evidence of atomic-like transitions
- Spectral line-widths not limited by inhomogeneous broadening due to structural variations
- Investigate correlations effects

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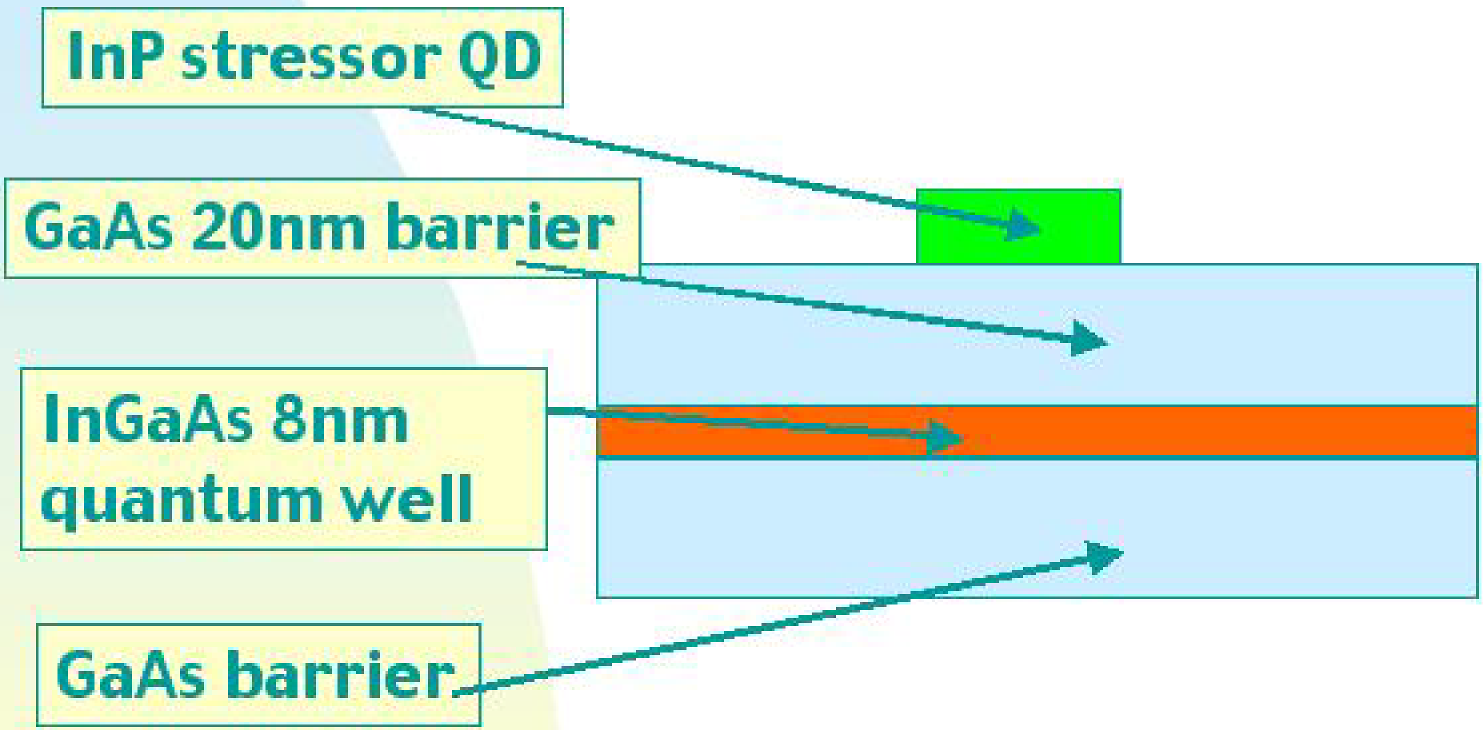
R. Rinaldi, S. Antonaci, M. DeVittorio, R. Cingolani, U. Hohenester, E. Molinari, Harri Lipsanen and Jukka Tulkki, Phys. Rev. B62, 1592 (2000)

Schematic of heterostructure



Grown by molecular vapor phase epitaxy

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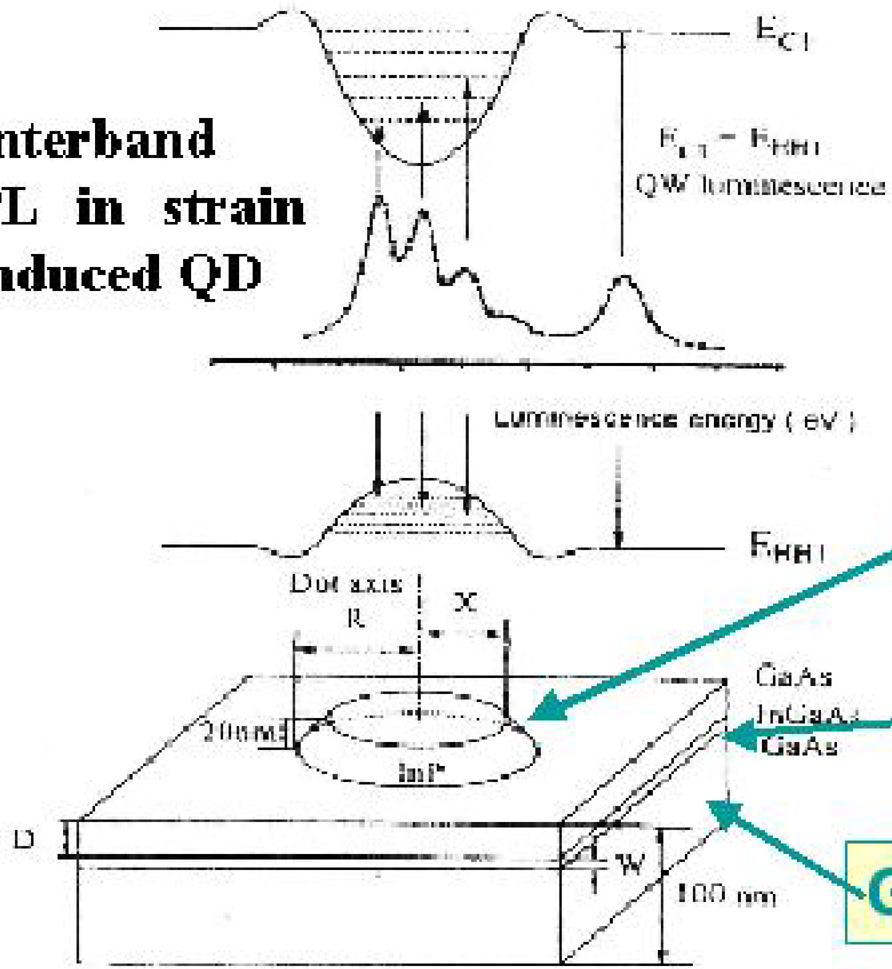
Stressor to create quantum confinement in InGaAs quantum well

Parabolic-like strain potential laterally confines the carriers in the InGaAs QW under stressor.

Interband PL in strain induced QD



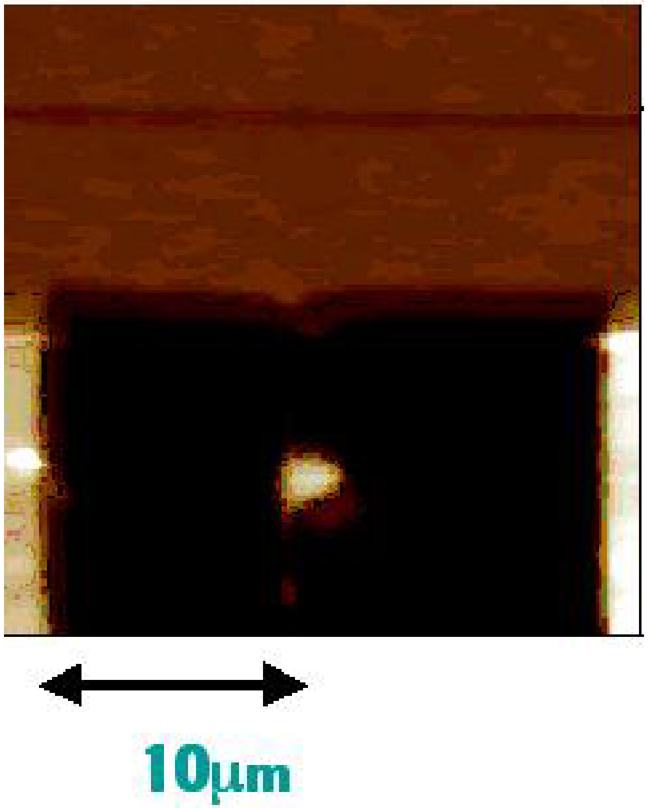
InP stressor QD

InGaAs quantum well

GaAs barrier

Sample processing

To achieve spatial resolution physically isolate QD .
By nanolithography, using an atomic force microscope and HCl wet etching, create a mesa structure



Mesa structure to isolate dots

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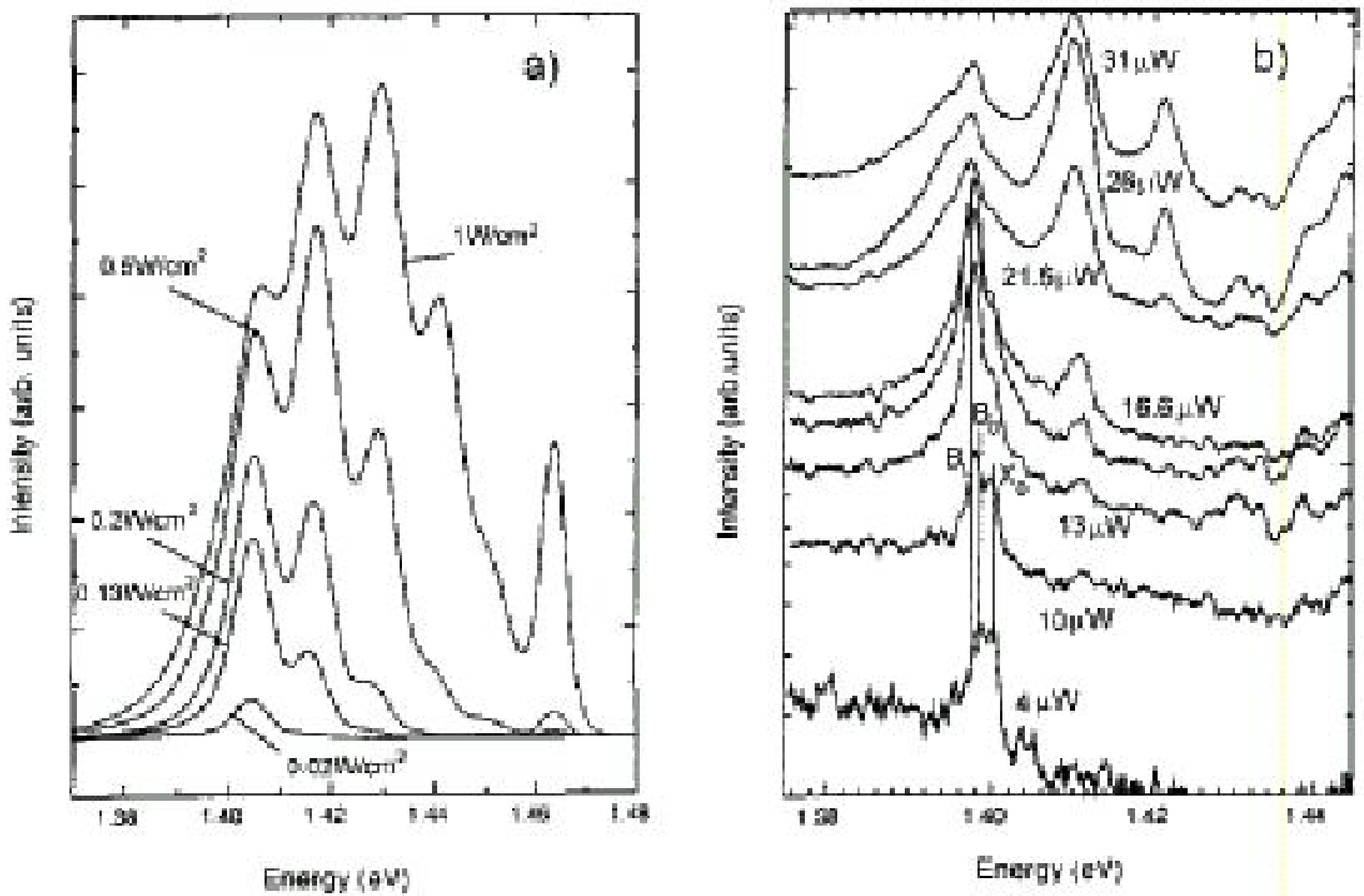
Power intensity dependent PL spectra at 20K



R. Rinaldi, S. Antonaci, M. DeVittorio, R. Cingolani, U. Hohenester, E. Molinari, Harri Lipsanen and Jukka Tulkki, Phys. Rev. B62, 1592 (2000)

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Experimentally observed

Ensemble PL:

1Σ (ground state)

1Π, 2Σ, 2Π (excited states)

FWHM : ~ 7meV

Single QD:

1Σ (ground state)

1Π, 2Σ, 2Π (excited states)

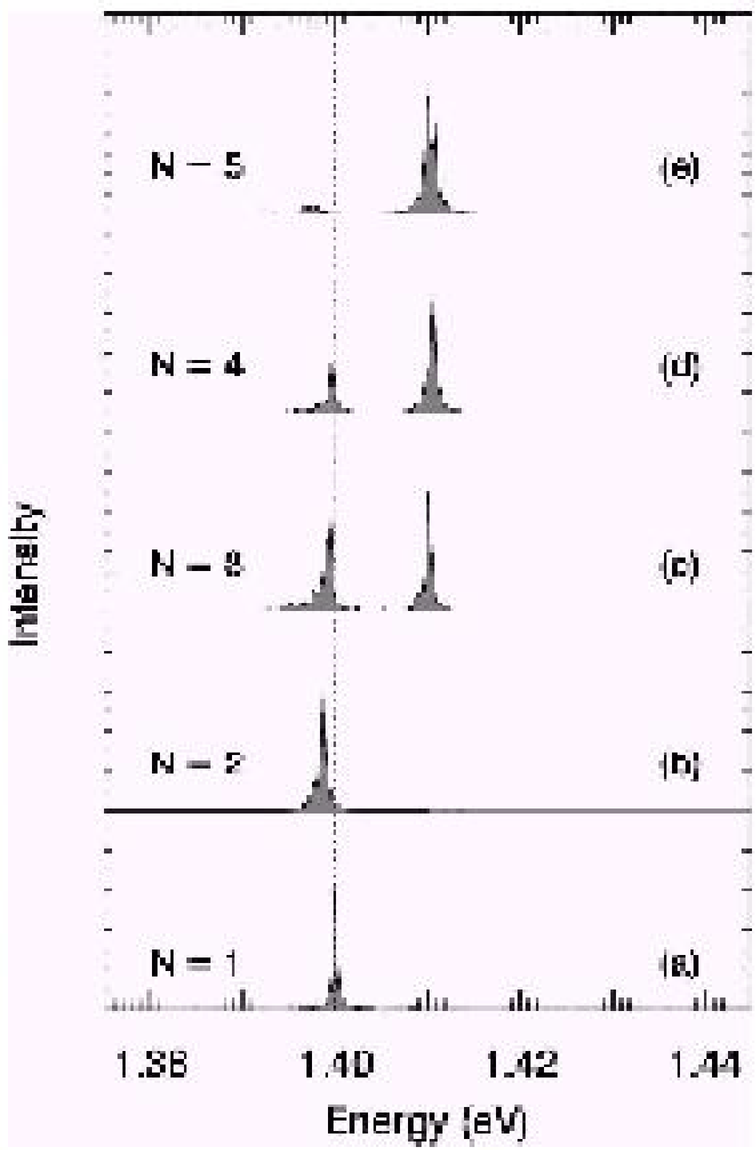
FWHM : ~ 0.8 meV

Many particle interactions

- **Luminescence involves the removal one e-h pair from the interacting many-particle system, and one photon is created.**

$$I(\omega) \propto \sum_{n,n'} f_T(E_n^N) |\langle n';N-1|\hat{\pi}|n;N\rangle|^2 \mathcal{D}_\gamma(\omega - E_n^N + E_{n'}^{N-1}).$$

The single-particle states derived by solving single-particle Schrodinger equation within the envelope-function and effective-mass approximations.



1Σ bi–excitons of spin up and
and tri–exciton of spin up

1Σ bi–excitons of spin up and
spin down and tri–exciton

1Σ bi–exciton of spin up
and 1Σ excitons spin down

1Σ excitons of spin up
and spin down

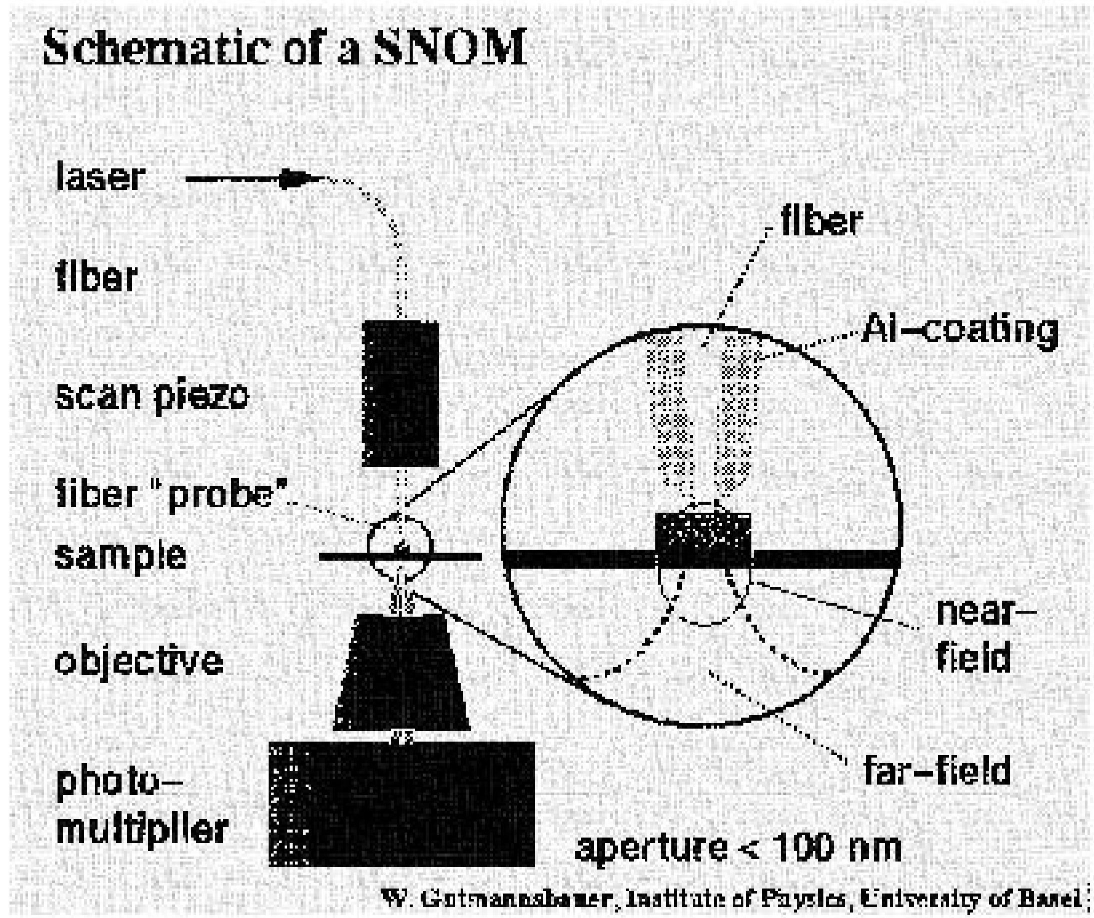
1Σ exciton

Conclusions

- Agreement between experiment and theory confirms that photoexcited electrons and holes are strongly confined in the QD
- QD behaves as an artificial atom
- Confinement induces a strong exciton binding energy and significant coupling between excitons

Scanning near-field optical microscopy

- low temperature (20 –300K) SNOM of aperture type (optical fibre)
- Spatial resolution 100nm



M. Lomascolo, University of Lecce, Lecce Italy
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Single dot phololuminescence of $In_{0.50}Ga_{0.50}As$ QDs formed by self assembly

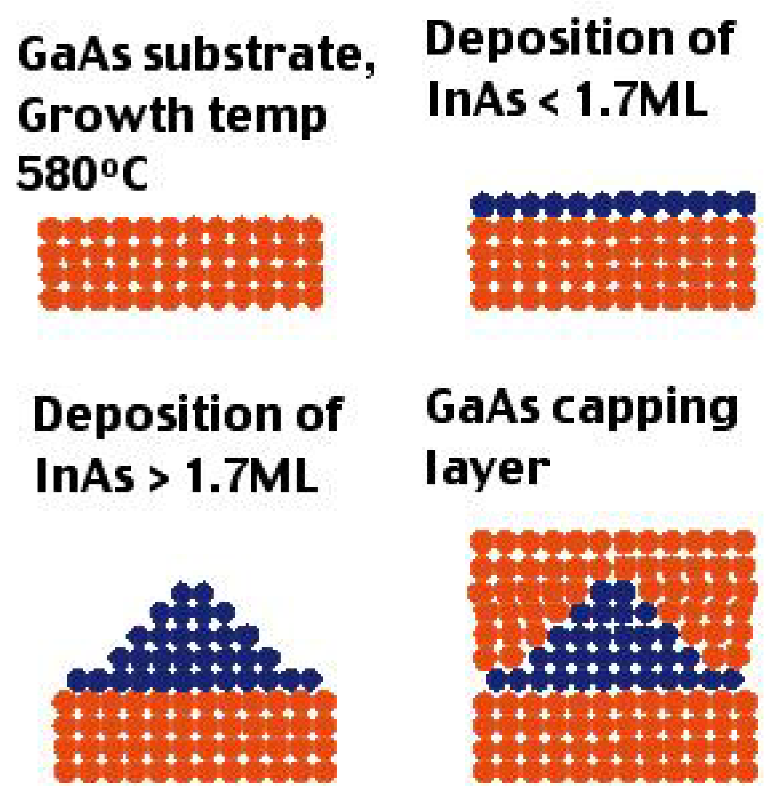
Isolate a single QD by a combination of electron beam lithography and HCl etching

Near field excitation

Far field collection by cooled Si CCD

Self assembled, strain driven InGaAs QD growth

- Stranski-Krastinov, beyond critical thickness, 2D-3D transition, coherently strained islands
- Narrow size and shape distribution
- Growth process is thermodynamically driven, long range elastic interaction



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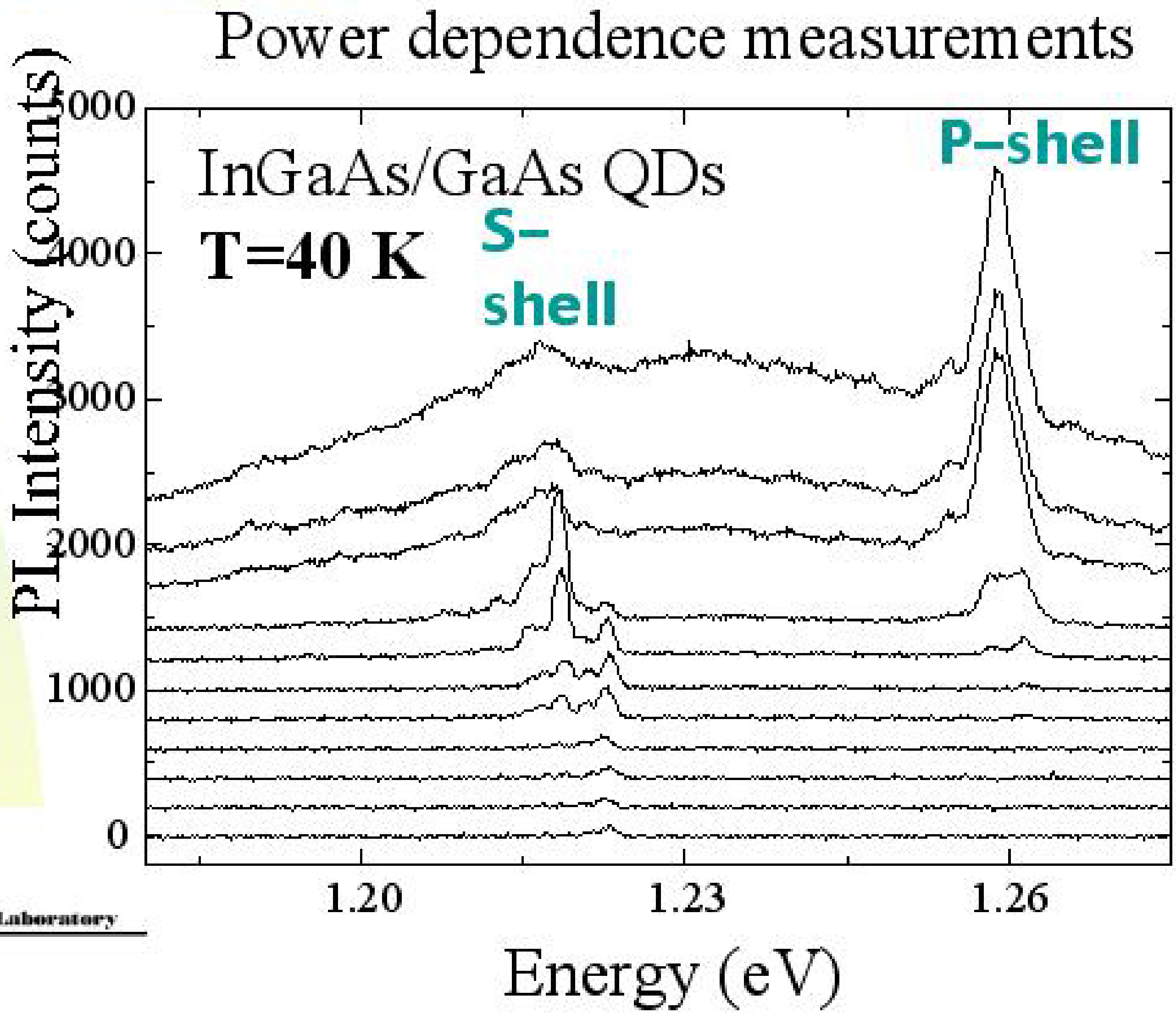
V.A. Shchukin and D. Bimberg, Rev. Of Mod. Phys. 71 (1999) 1125

SNOM spectra from InGaAs quantum dots

Illumination by Ar laser, 488nm line

Power dependence measurements from 0.2 to 9 microWatts



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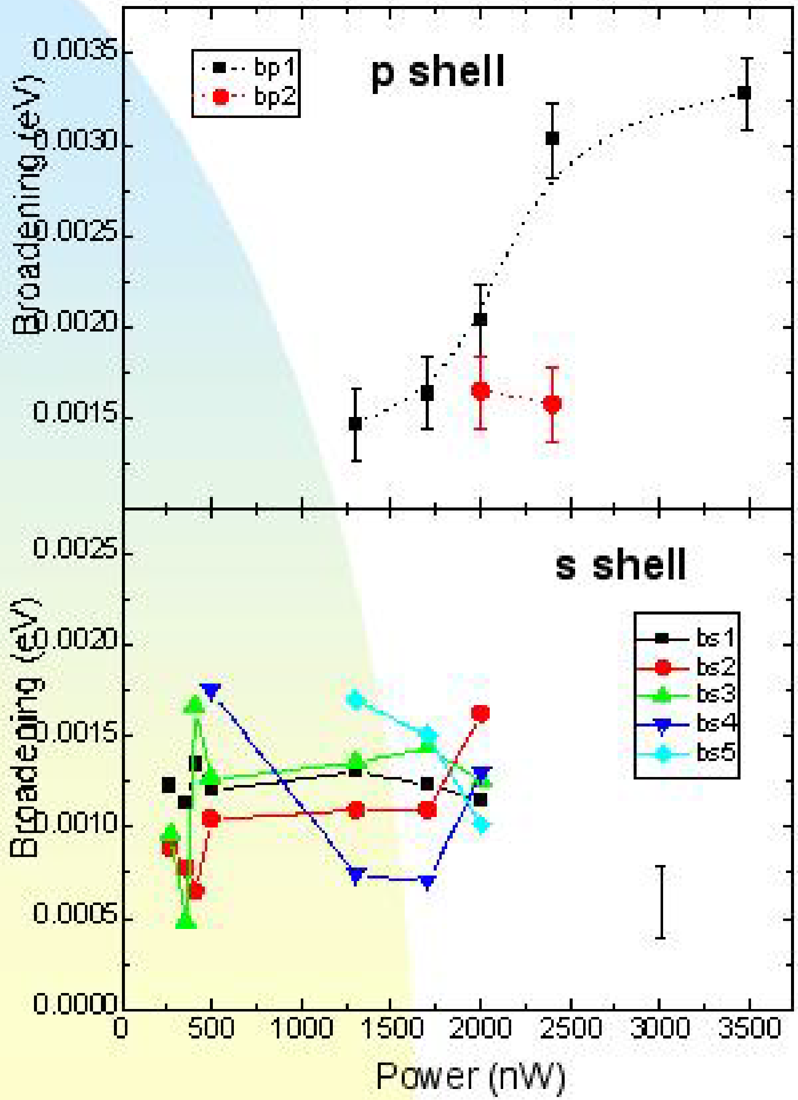
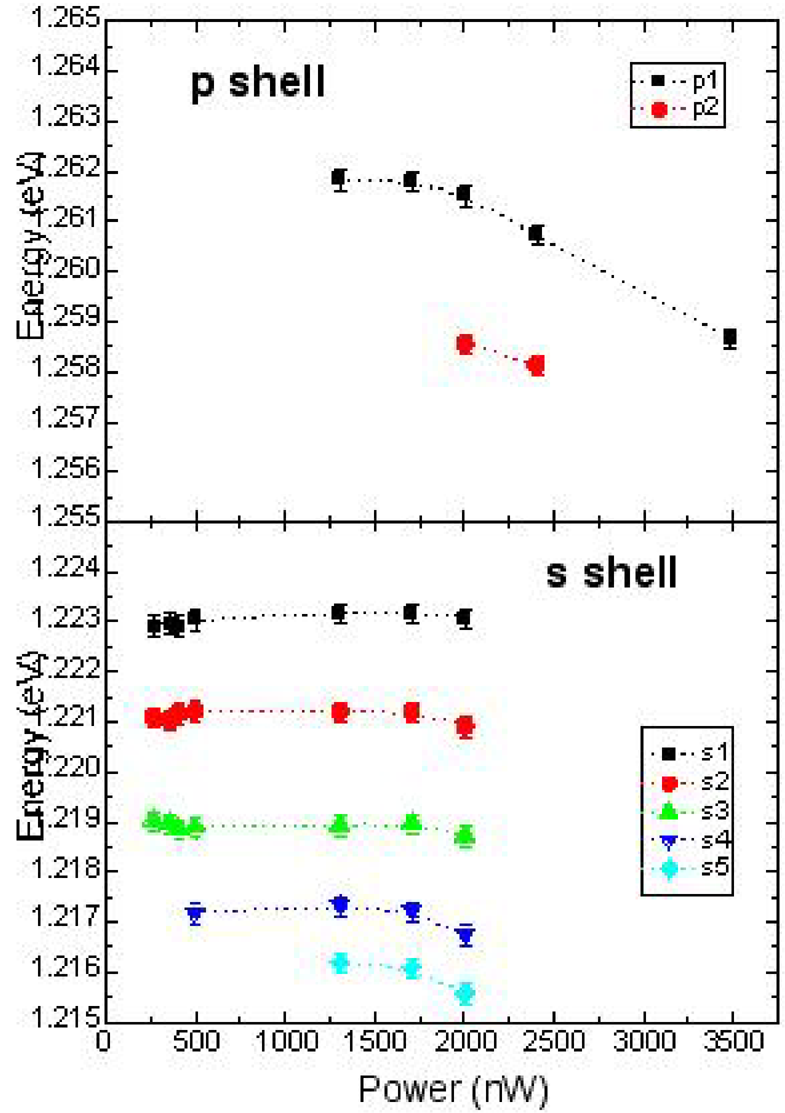
Line-width broadening



Peak position



Conclusions

- Power intensity dependence shows:
  - At lowest powers S-shell neutral excitonic emission.
  - Increasing power appearance evolution of biexciton and charged exciton emission.
  - State-filling phenomena evident with the appearance of the P-shell emission
  - Red shift of biexcitons and charged excitons