# Electronic and optical properties of quantum dots

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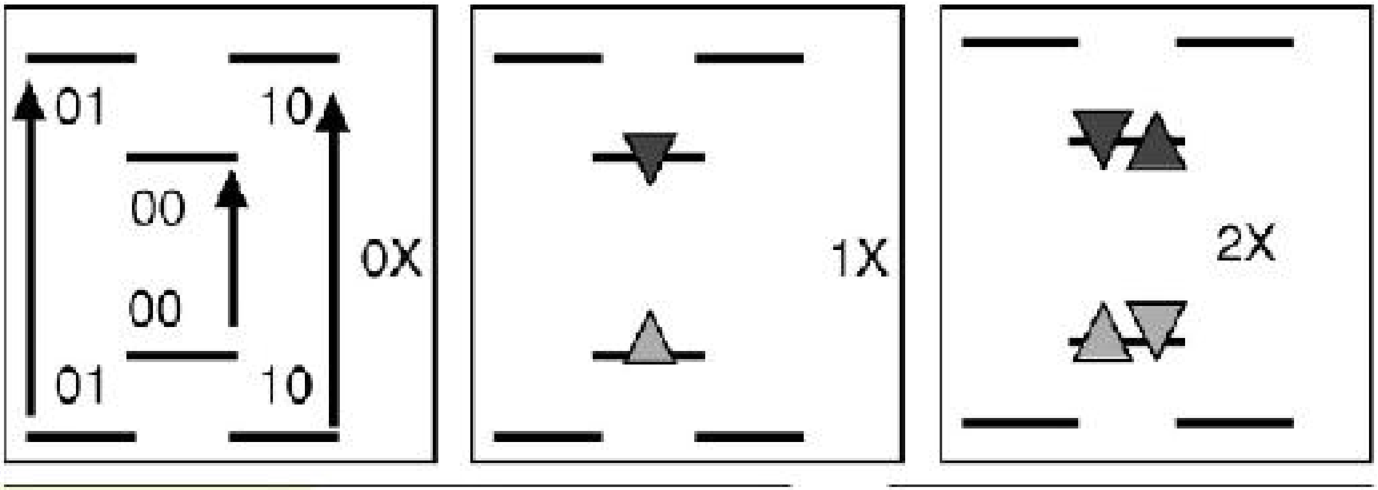
# Outline of lectures

- 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

# Multi-particle interactions




**Exciton** **Bi-exciton**

# Scanning tunneling spectroscopy of single $In_{0.5}Ga_{0.5}As$ quantum dots

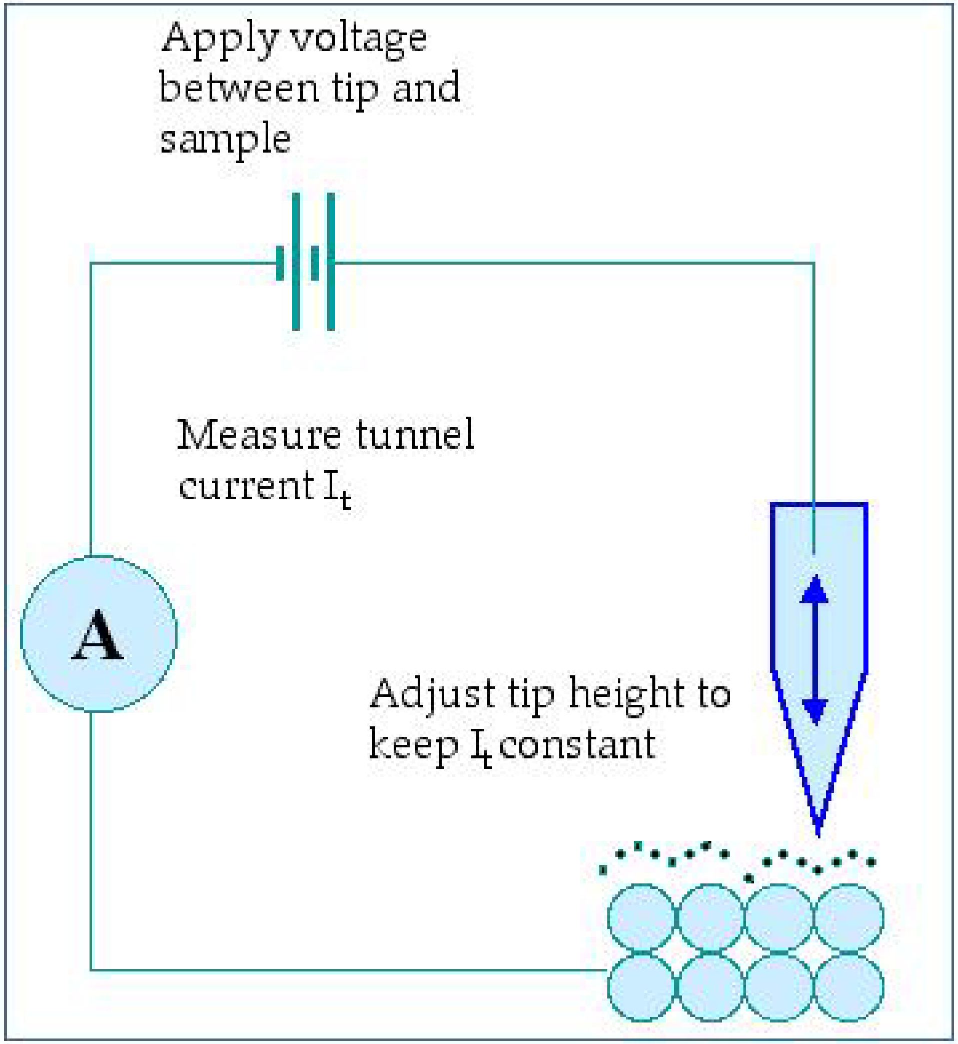
- Tunnel into the discrete, localized states of the quantum dot
- Examine spatial maps of the tunneling current
- Seek to map the spatial distribution of charge density associated with QD states

# Tunneling current spectroscopy

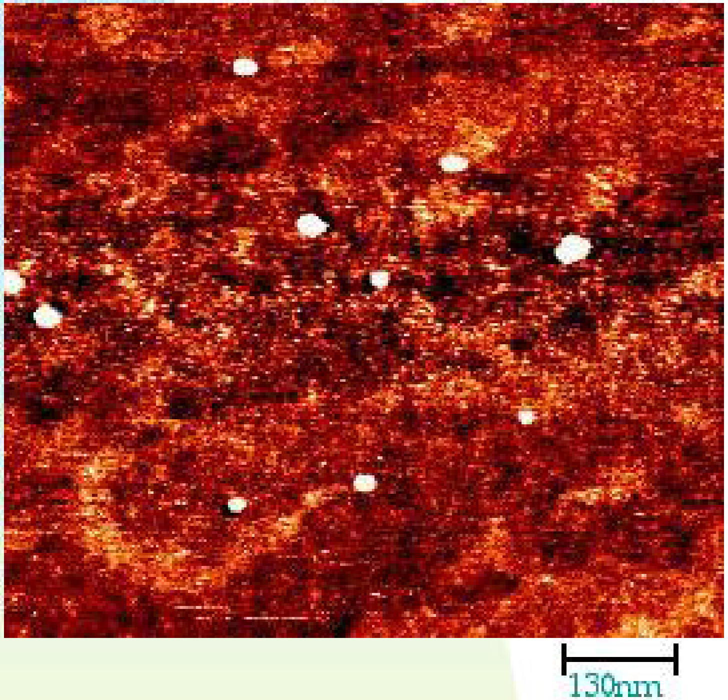
**To a very first approximation the tunneling current can be represented by**

$$I \propto \int_0^{eV} \rho_t(V - E)\rho_s(E)D(E)dE$$

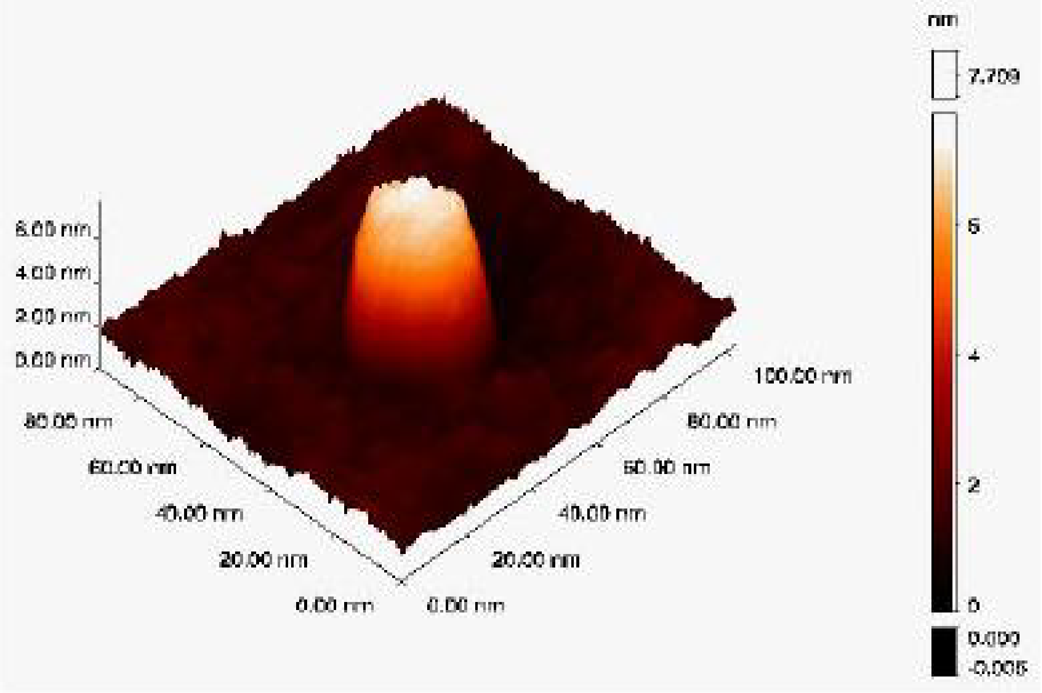
**where $\rho(E)$ is the sample density of states and $D(E)$ is the tunneling transition probability.**



# Surface topography of uncapped InGaAs quantum dots




- Dot density is sufficiently low ($3 \times 10^9$ $cm^{-2}$) -- no interaction between dots
- Octagonal base, side-walls combination of {111} and {110} facet planes

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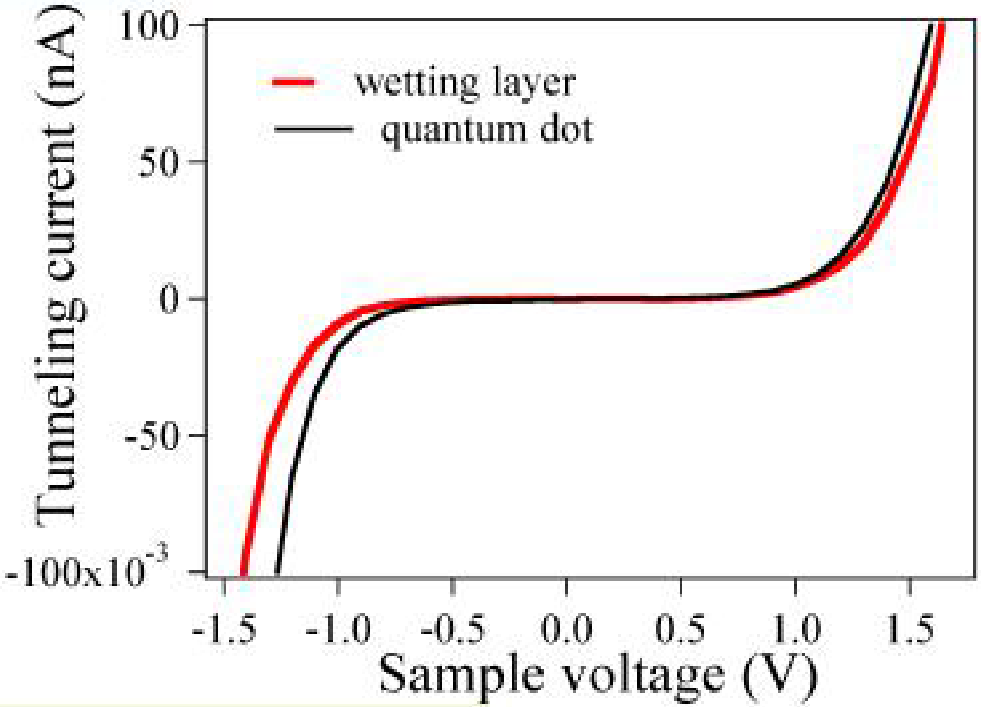
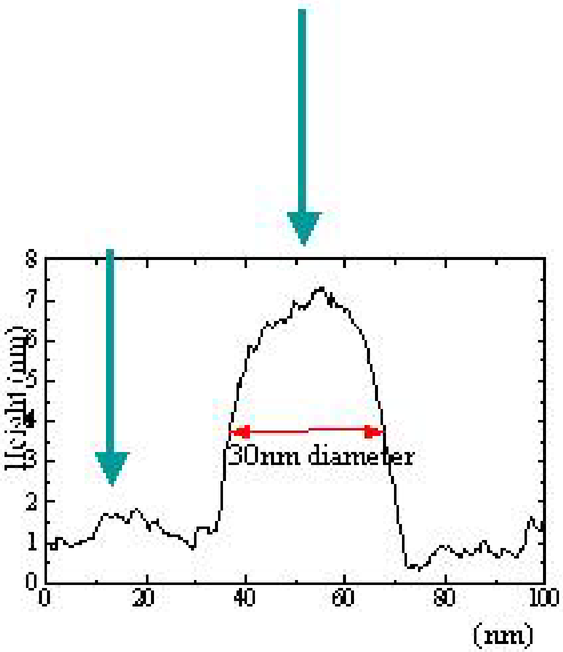
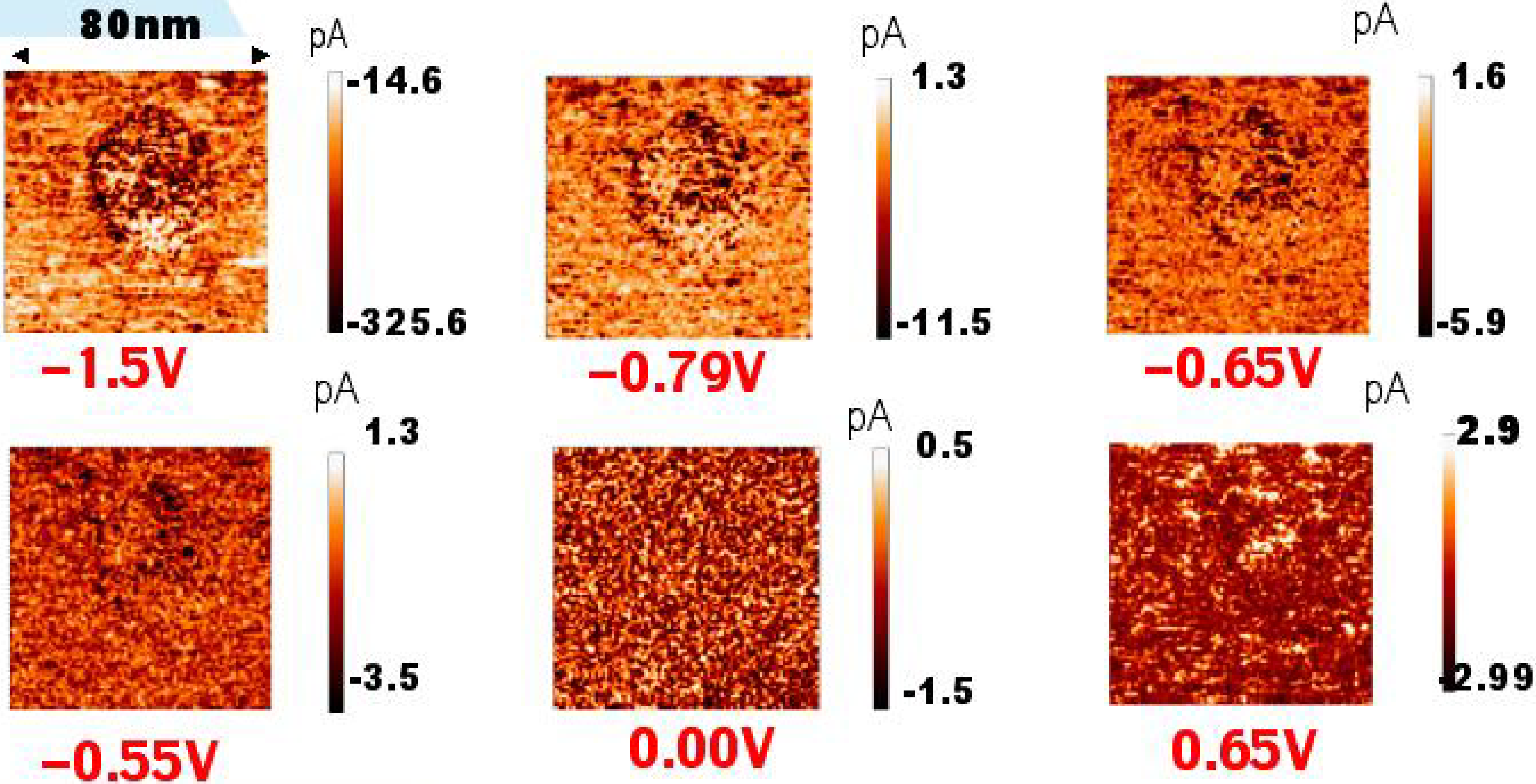
# Tunneling current spectra



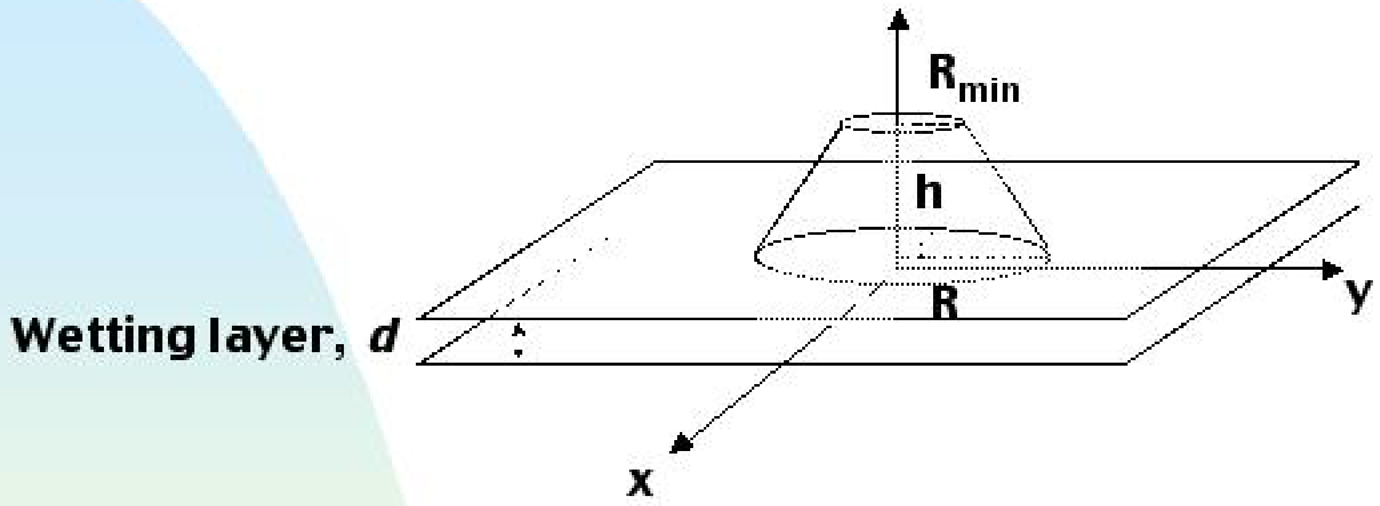

**Tip position**



# Current imaging tunneling spectroscopy of a single quantum dot



# A phenomenological approach




Assume the QD shape is a truncated cone, *because of the* **cylindrical symmetry** can solve the Schrodinger equation analytically,

$$\psi_{nl}(\bar{r}) = \frac{e^{il\vartheta}}{\sqrt{2\pi}}\psi_{nl}(\rho, z)$$

with $l=0$ for S-like levels, $l=\pm 1$ for P-like levels...

*For the bound levels we consider the* **separable form**

**Single particle wavefunction**

**Envelope function**

$$\psi_{nlp}(\rho, z) = F_{nl}(\rho)\varphi_{nlp}(z)$$

$$F_{nl}(\rho) = N_{nl}\rho^{|l|}P_{nl}(\rho^2)\exp\left(-\frac{\rho^2}{2\beta_{nl}^2}\right)$$

$$P_{nl}(\rho^2) = \sum_{p=0}^{n-1} a_{p,(nl)}\rho^{2p}$$

Where $N_{nl}$ are normalization constants and $a_{0,nl}=1$, the coefficients are obtained by othornormalization.

# Calculating the tunneling current

**Following Tersoff and Hammer**

$$I \approx \sum_{n,l,j} g_l \left[\frac{1}{1+e^{-\beta E_{nlj}}} - \frac{1}{1+e^{-\beta(E_{nlj}-\phi)}}\right] \left|F_{nlj}(\mathbf{r}_t)\right|^2 +$$

$$\frac{S}{4\pi^2}\int d^2k \left[\frac{1}{1+e^{-\beta E_{\mathbf{k}}}} - \frac{1}{1+e^{-\beta(E_{\mathbf{k}}-\phi)}}\right] \left|\psi_{\mathbf{k}}(\mathbf{r}_t)\right|^2$$

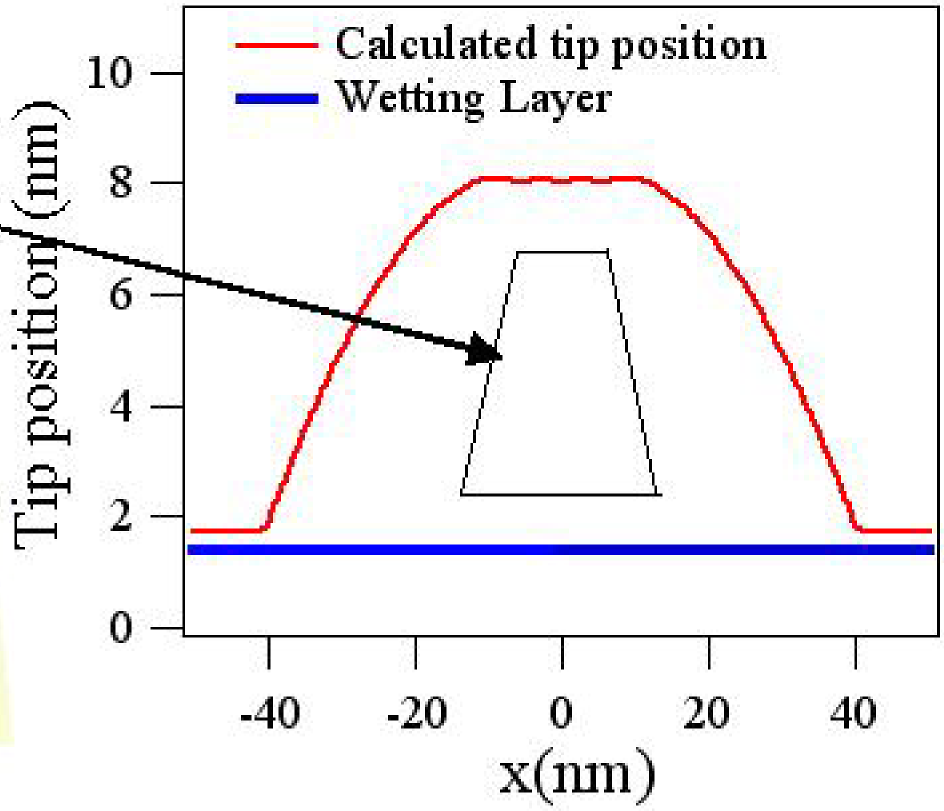
for the tunnelling current, where n, l, j are the quantum numbers labelling the dot bound states, **k** is the 2D wavevector of the wetting layer eigenstates and $\phi = \mu_{dot} - \mu_{tip}$

$$\langle \mathbf{r} | \psi_{\mathbf{k}} \rangle = \langle \mathbf{r} | \mathrm{wl}, \mathbf{k} \rangle - \sum_{nlj} \langle \mathbf{r} | F_{nlj} \rangle \langle F_{nlj} | \mathrm{wl}, \mathbf{k} \rangle$$

$$\langle \mathbf{r} | \mathrm{wl}, \mathbf{k} \rangle = \frac{1}{\sqrt{S}} \exp(i\mathbf{k}.\rho)\chi_{wl}(z)$$

# Simulating QD topography

**QD size from STM measurement**

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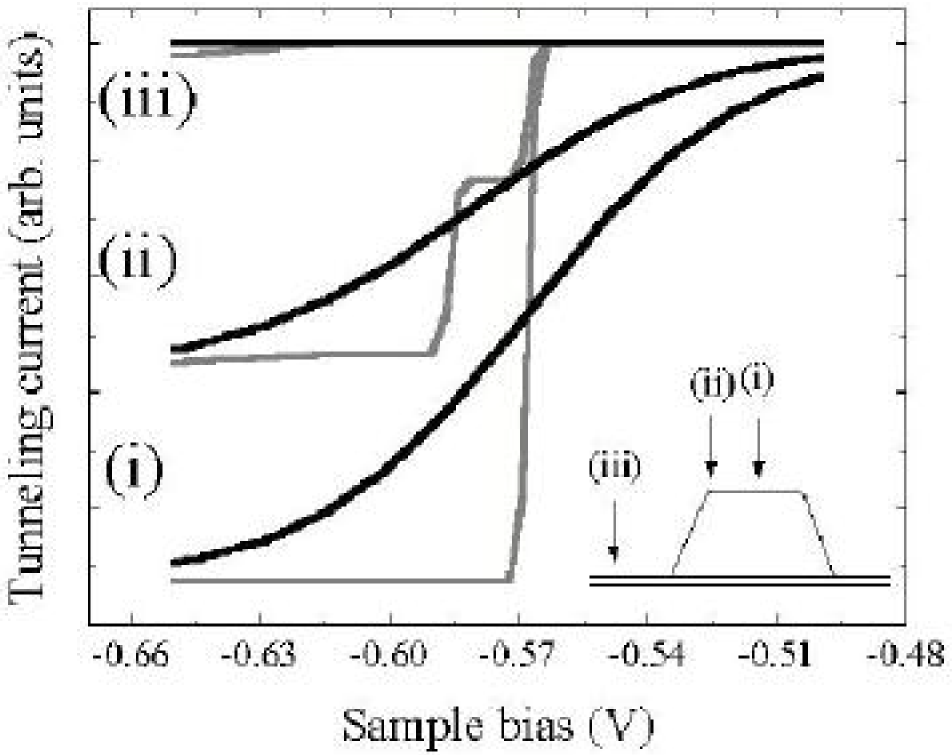
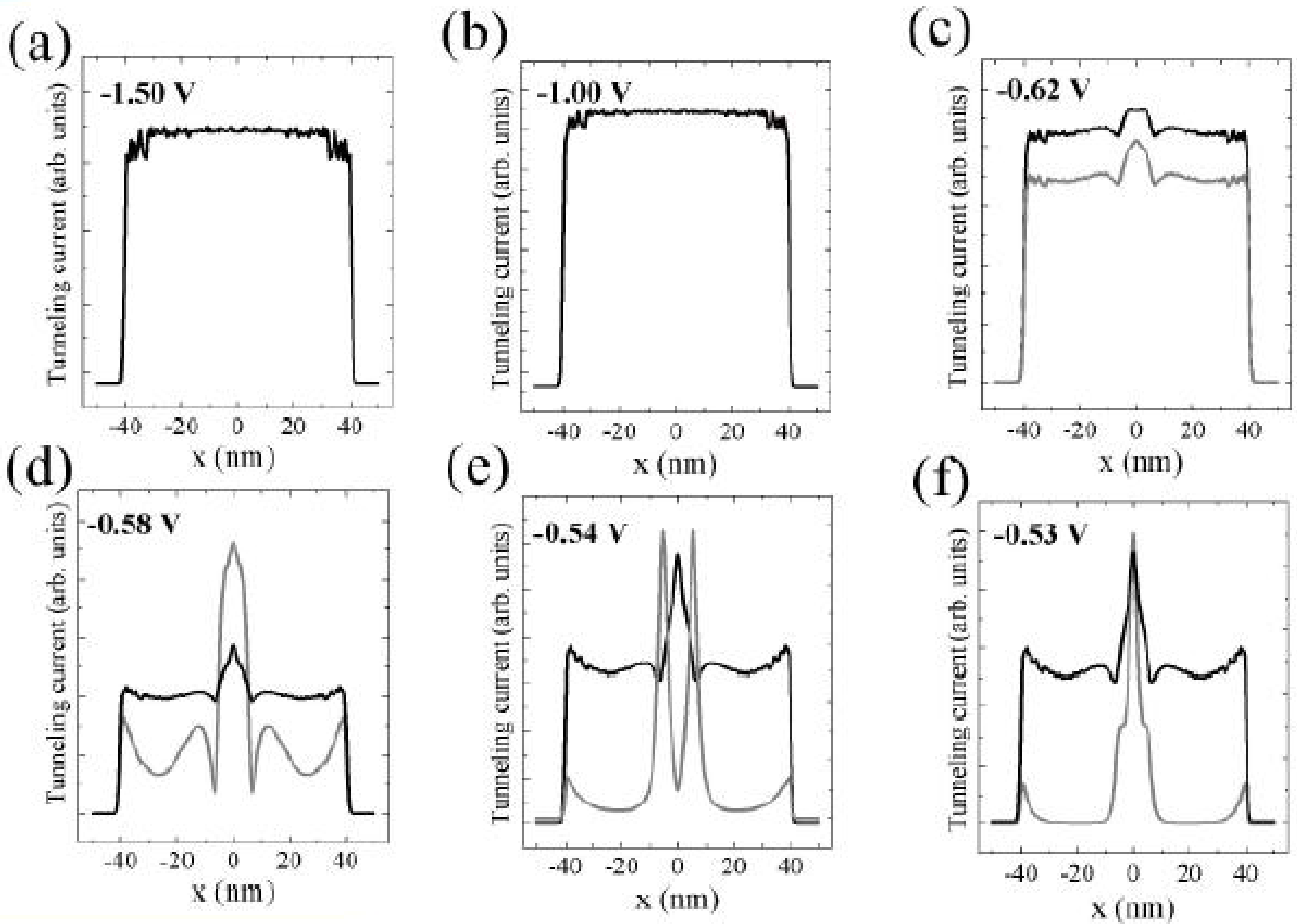
# Calculated tunneling current spectra

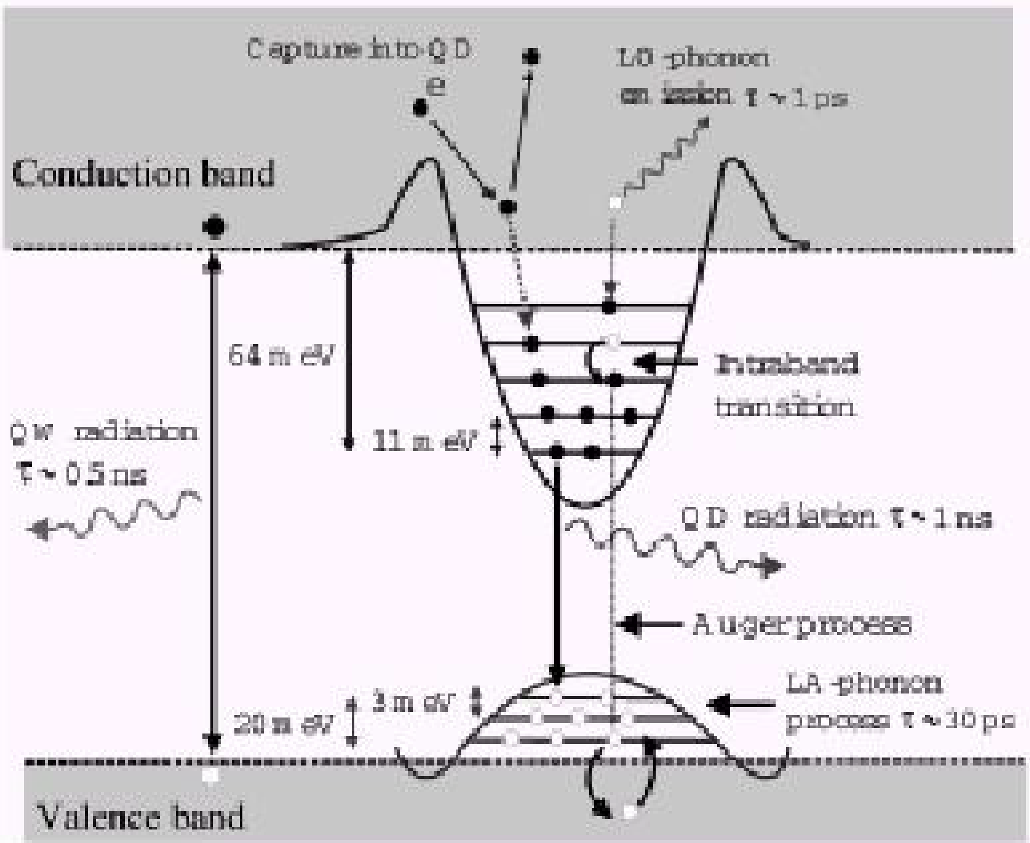
- Spatially resolved calculation
- Higher intensity at center of QD
- Reduced tunneling current in WL region



# Calculated tunneling current profiles



# The relaxation processes

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# Origins of observed current contrast

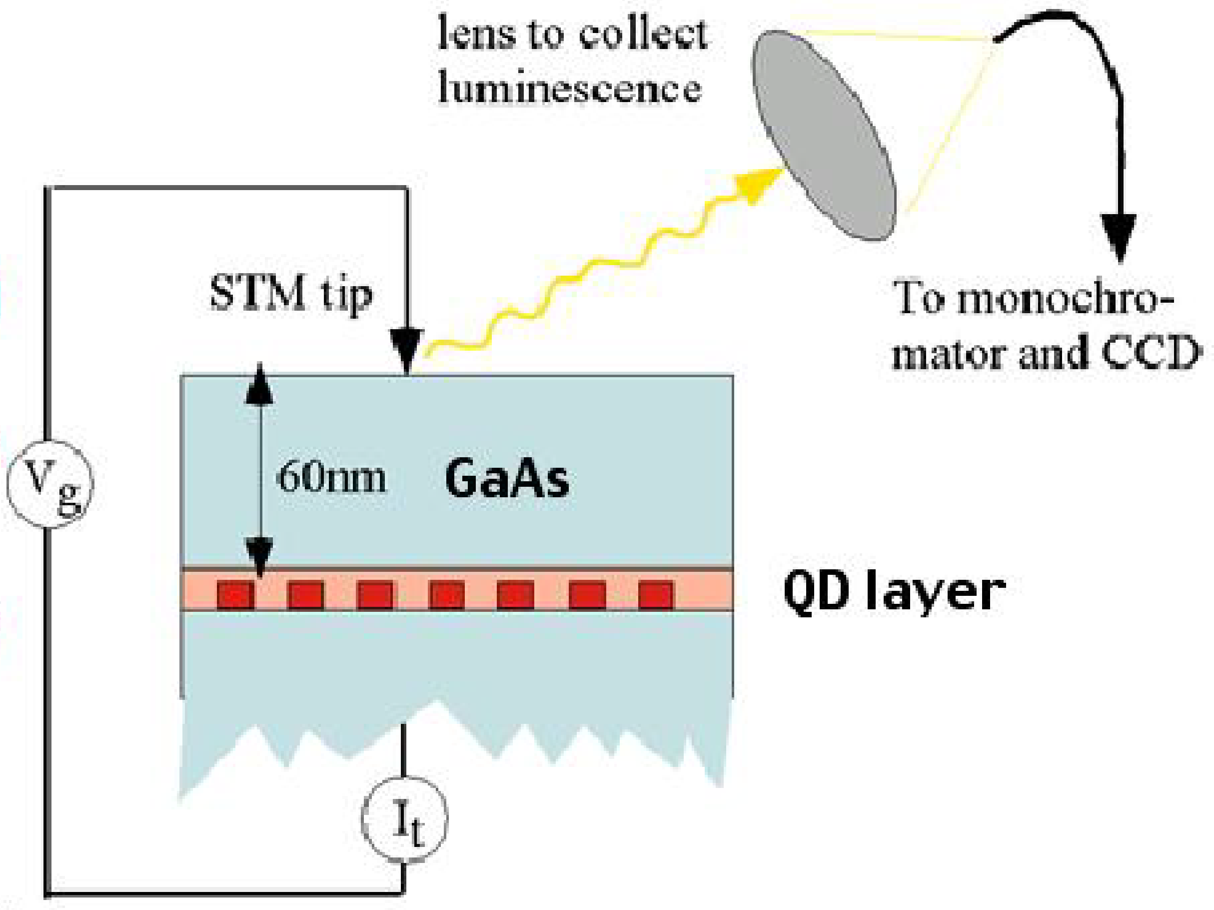
- Measure a permanent current due to exchange of carriers with host
  - Thermal activation
  - Tunneling into WL
- “Unoccupied levels” are already filled
  - *N*-type doped material, a reservoir of electrons
  - Inevitable high density of surface defect states
- Charging of the dots
  - Addition energy
  - Perturbing the system

# Tunneling current induced luminescence of InGaAs QDs

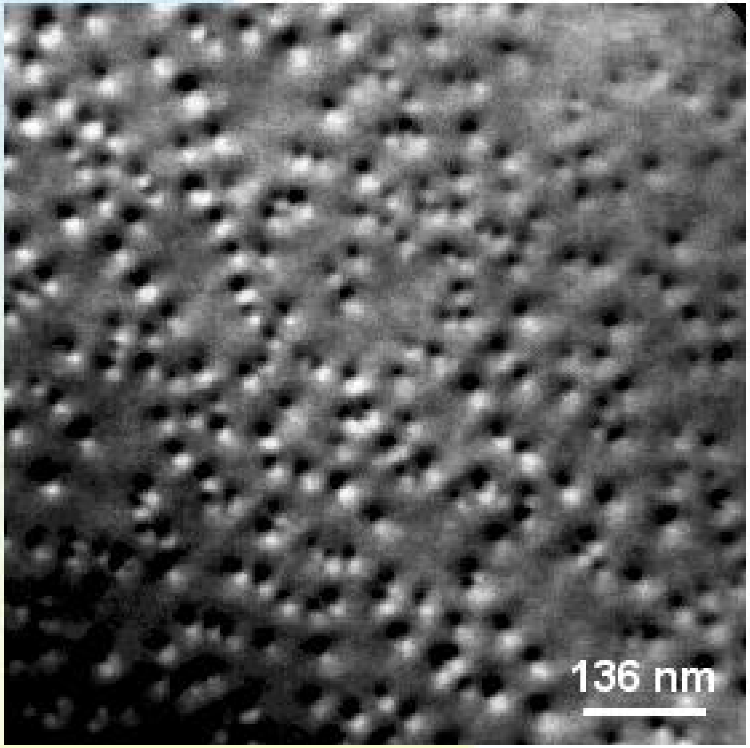
- Combine
  - Controlled carrier injection of STM
  - With luminescence
- Seek
  - Influence of electrical injection into QD - similar to mini-laser device structure
  - To understand the influence of hole-hole correlation effects in multi-particle systems

# Experimental set up

- Optical fibre collection of signal
- 0.3m monochromator
- Cooled Si charge coupled device
- Spectral resolution in the region of 1000nm is 0.25meV
- All measurements made at 70K in UHV conditions.

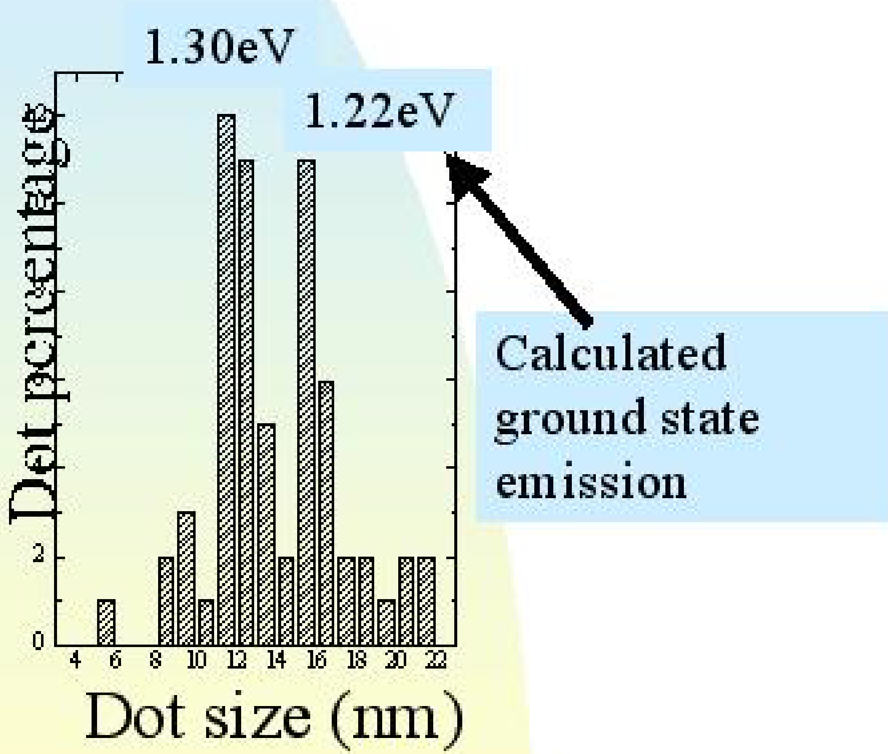


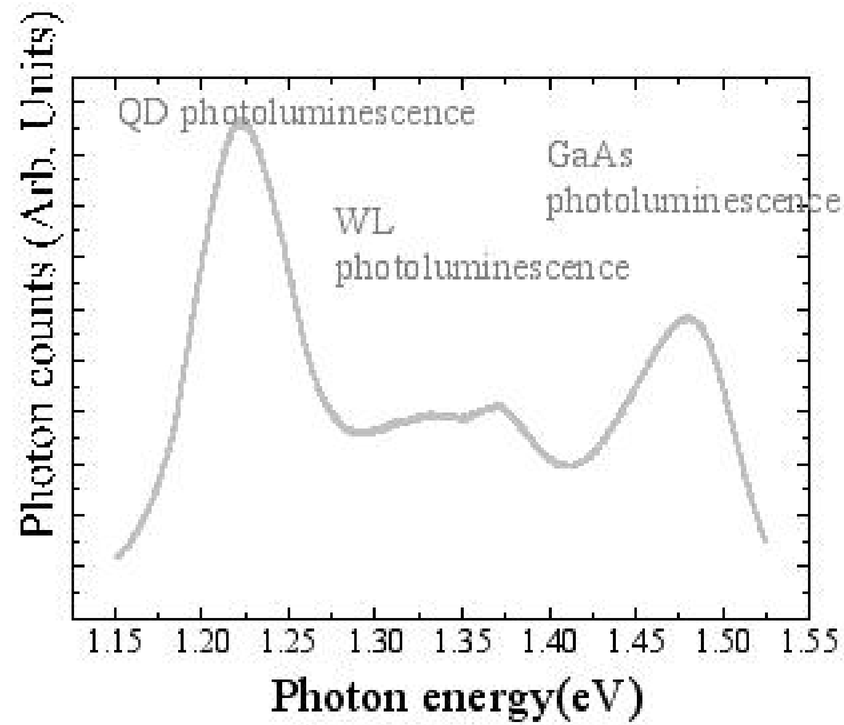
# Planar-view dark-field TEM image of capped sample



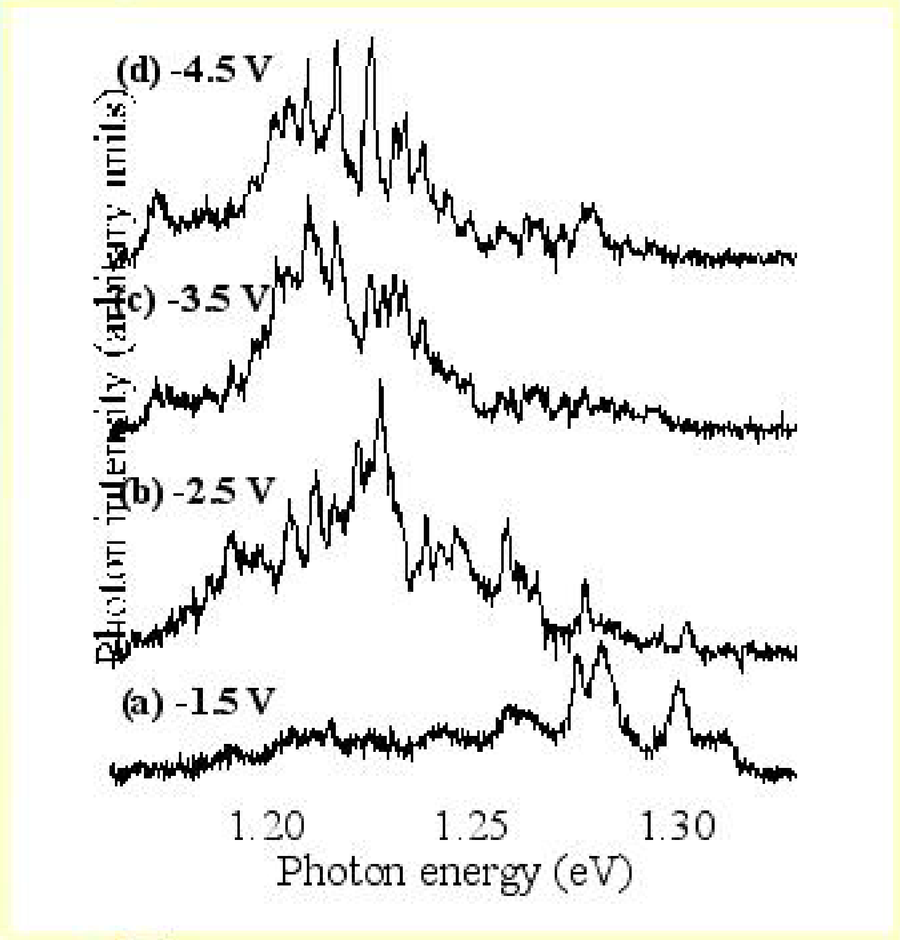

- No extended defects
- Dot density: $4x10^{10}/cm^2$
- Large distribution of sizes--two main families of QD radii

# Comparing structural statistics extracted from the TEM measurements to ensemble photoluminescence



# Voltage dependence of STM-induced luminescence




- Tunneling current of 0.5nA.
- STM induced luminescence shows sharp lines, 2–4meV broad.
- Ballistic holes captured by QD via complex energy relaxation
- No evidence of shifts

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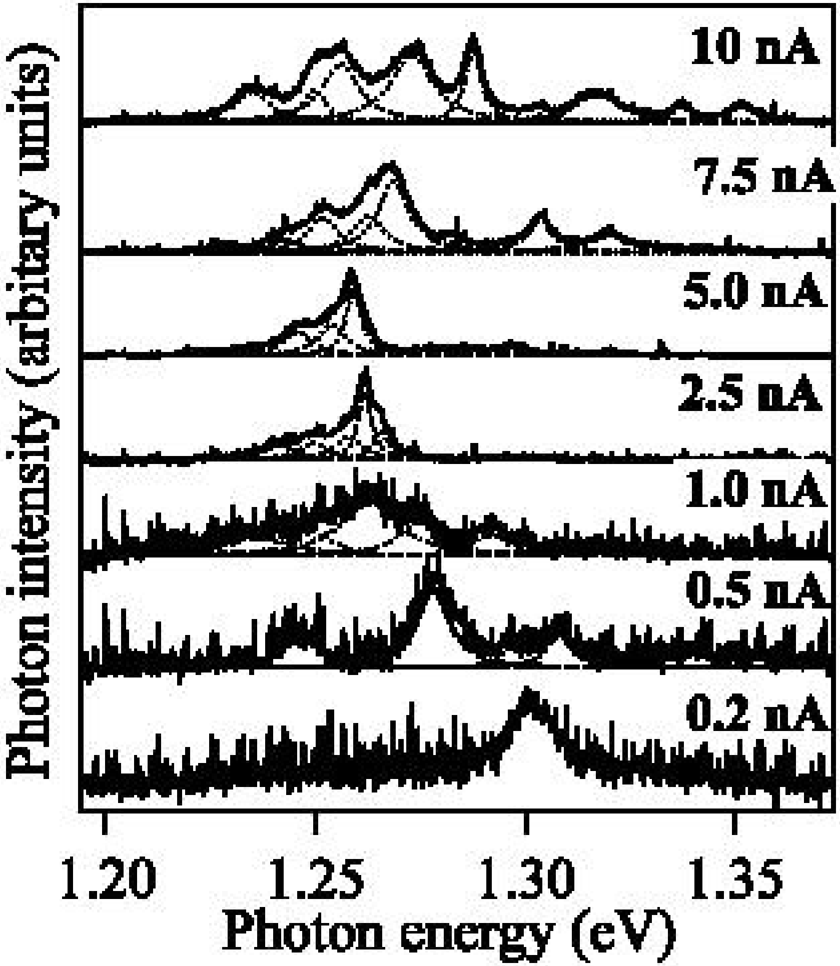
# Current dependence of STM-induced luminescence



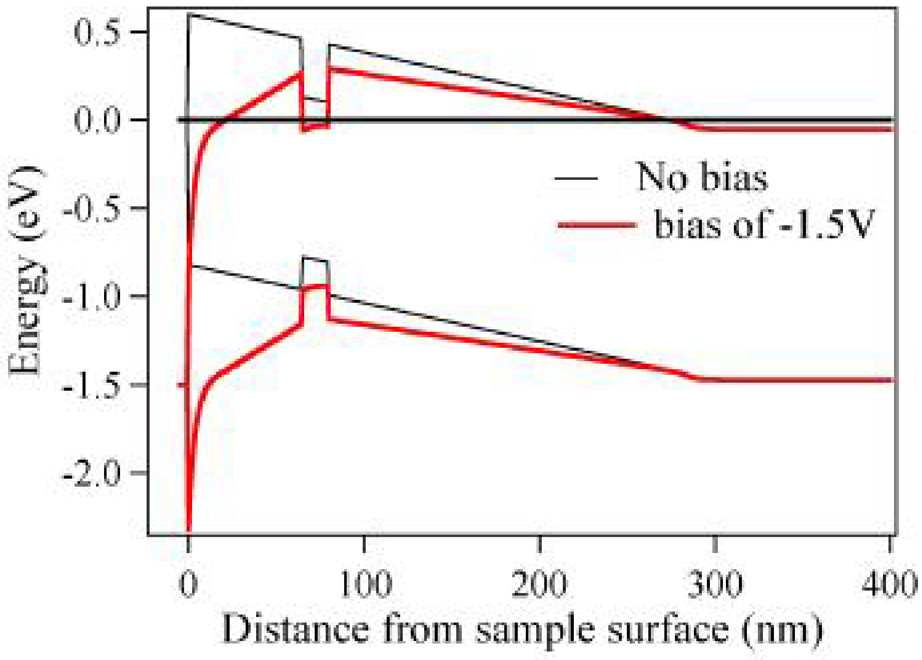

- Tunneling current dependent spectra, measured using a gap voltage of −1.5V
- Comparing with low power PL signal
- State filling effects are evident
- excited excitonic states appear with increasing tunneling current

# Mechanism of tunneling current induced luminescence

- Vacuum tunneling from tip to GaAs cap layer.
- Injection of holes into the GaAs cap layer.
- Transport within cap layer ballistic holes captured by WL states.
- Relaxation into QD states
- Radiative recombination.

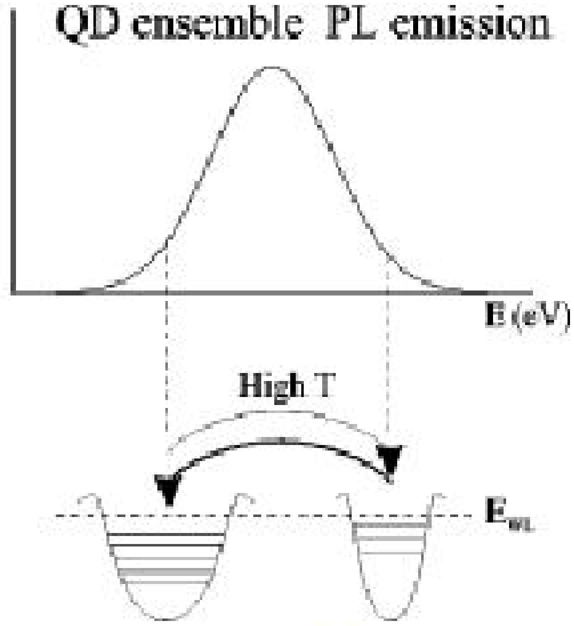
# What is happening??

- Luminescence observed only when
  - Injection of holes into the GaAs cap layer
  - tunneling out of occupied states -- hole injection
  - For voltages larger than -1.5V -- flat band conditions for radiative recombination




**Flat band conditions for luminescence**

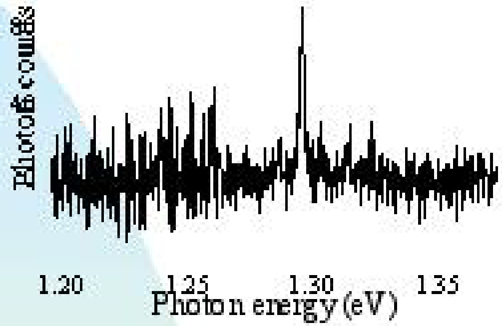
# From current and voltage dependence



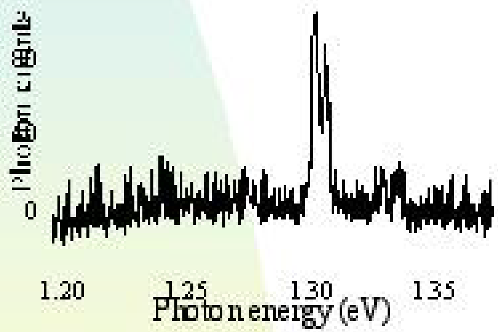

- Energy-loss processes promote mobility in the plane of the dots
- Initial capture by smaller dots
- Followed by occupation of other dots

# Spectra measured at different points

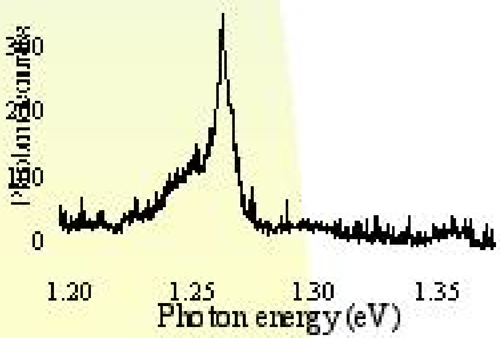
- Single dot spectra



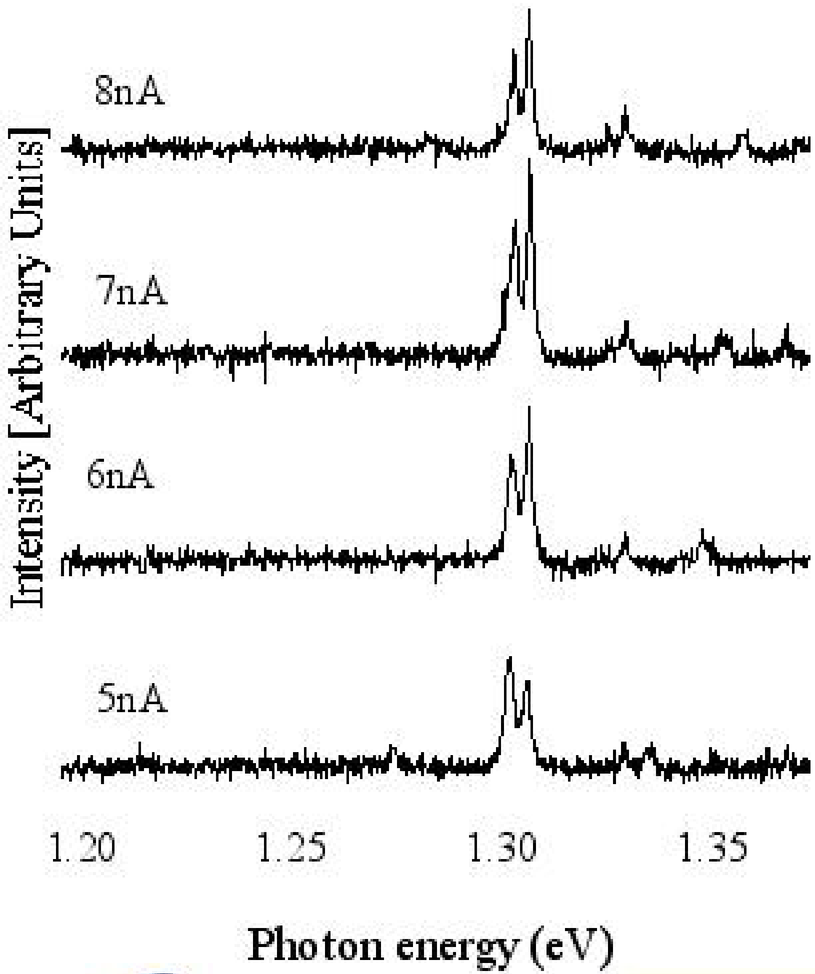

- Coupled quantum dots




- An ensemble of quantum dots



# Coupled quantum dots




- Symmetric and anti-symmetric bonding states of QD molecule
- With increasing tunneling current there is a change in relative intensity
- A blue shift with increasing hole current

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# Conclusions

- Complex hole relaxation processes--k-space scattering
- Inter dot tunneling seems evident due to the appearance of many sharp peaks in the luminescence spectra---formation of coupled dot states, artificial molecule-like states
- State filling effects, as QD states are occupied further injected holes compelled to fill other QD states.

**Research group led by**

**Prof. Roberto Cingolani**

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