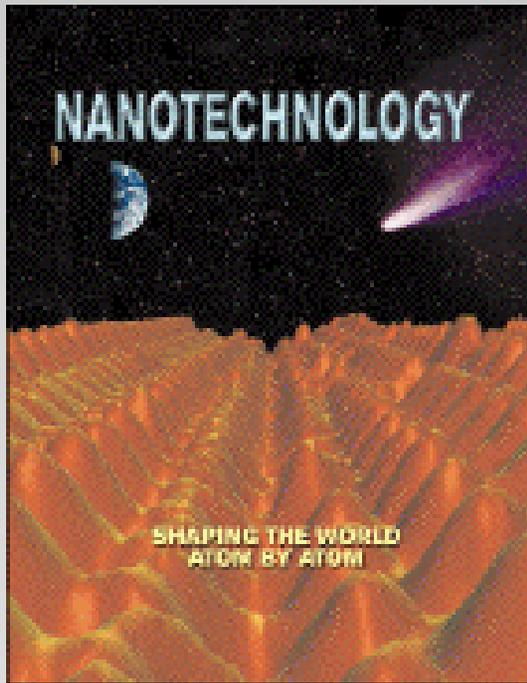




# Frontiers of Nanotechnology:

Evelyn L. Hu

California NanoSystems Institute  
UCSB



AIP 75TH ANNIVERSARY  
DIVERSE FRONTIERS OF SCIENCE SYMPOSIUM  
May 3, 2006

## Other Frontiers:

*Biological Engineering*, Angela Belcher, MIT

*Photo Optics*, Philip Bucksbaum, U. of Michigan

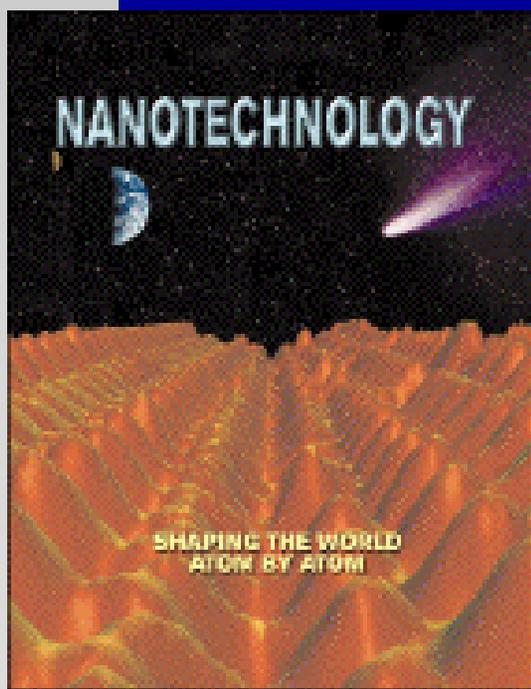
*String Theory*, Jim Gates, U. of Maryland

*Planetary Geophysics*, Raymond Jeanloz, UC Berkeley



# Frontiers of Nanotechnology: Broad Perspectives, Local Focus

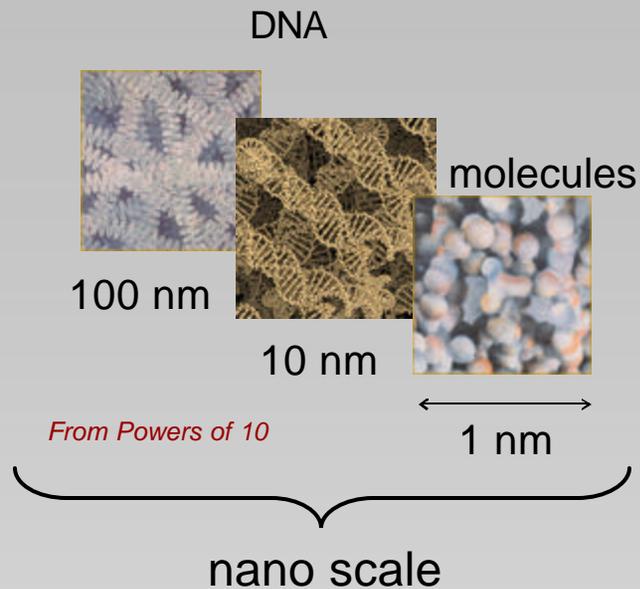
Evelyn L. Hu  
California NanoSystems Institute  
UCSB



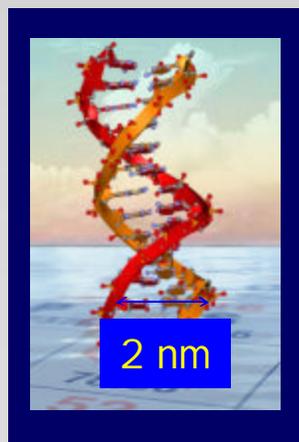
Solid State Sciences Committee  
October 20, 2006

For about a decade, Nanotechnology has been the focus of a U.S. (and international) focused initiative with exceptional coordination and integration. . .

# Nanotechnology: More Than Size Alone

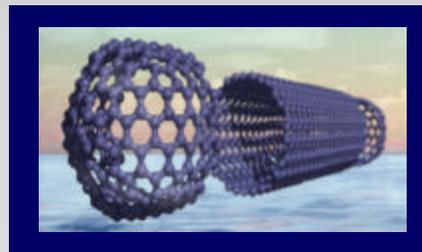


- Research at the atomic, molecular or macromolecular scale (1-100nm)
- Utilizing novel properties of materials at the nanometer scale
- Imaging, measuring, modeling, and manipulating matter at this length scale.

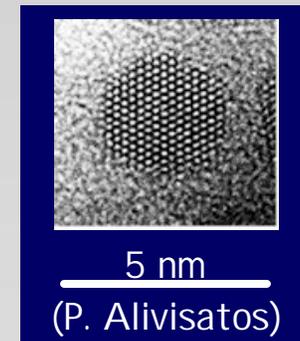


DNA

~1-2 nm

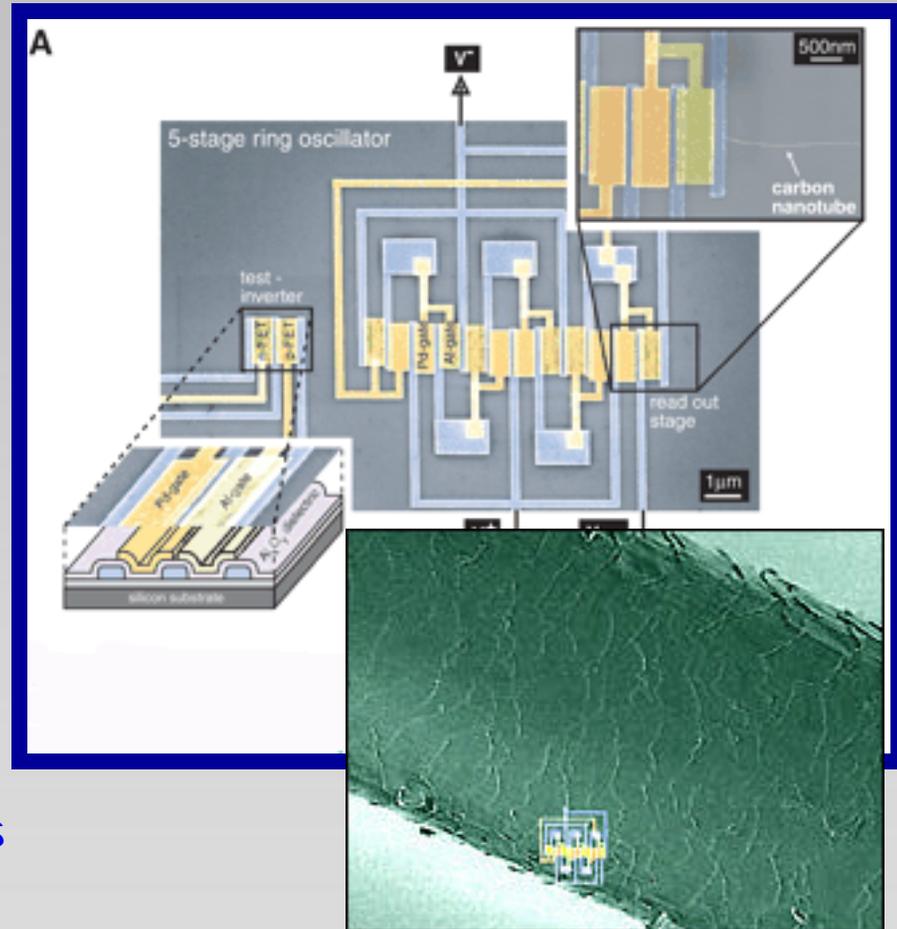
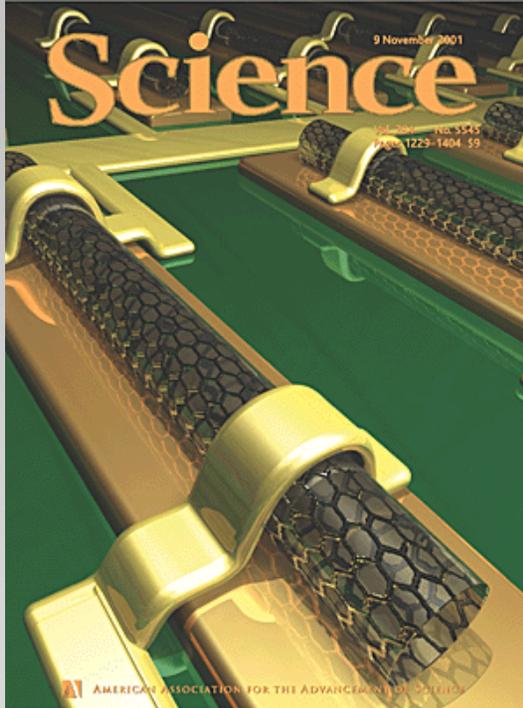


Carbon nanotube



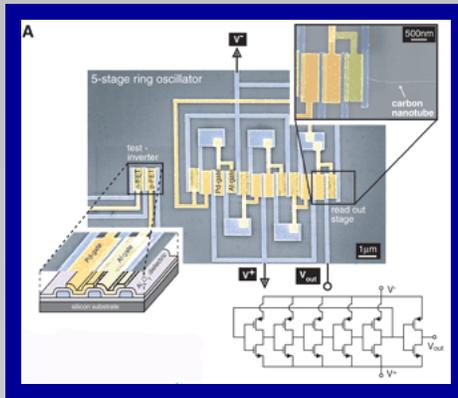
Nanocrystal, aka quantum dot

# New Nanoscale Building Blocks with exceptional properties

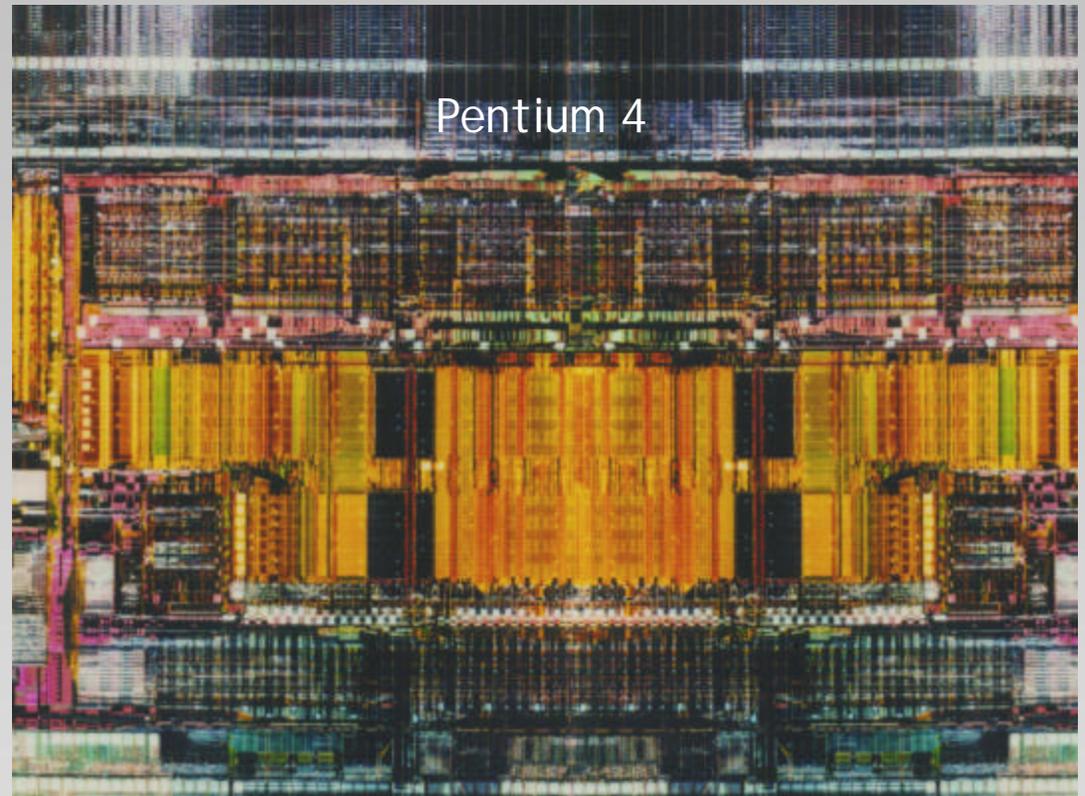


## Carbon Nanotubes as Transistors

'An Integrated Logic Circuit Assembled on a Single Carbon Nanotube',  
Chen et al., Science 311, 1735 (2006)



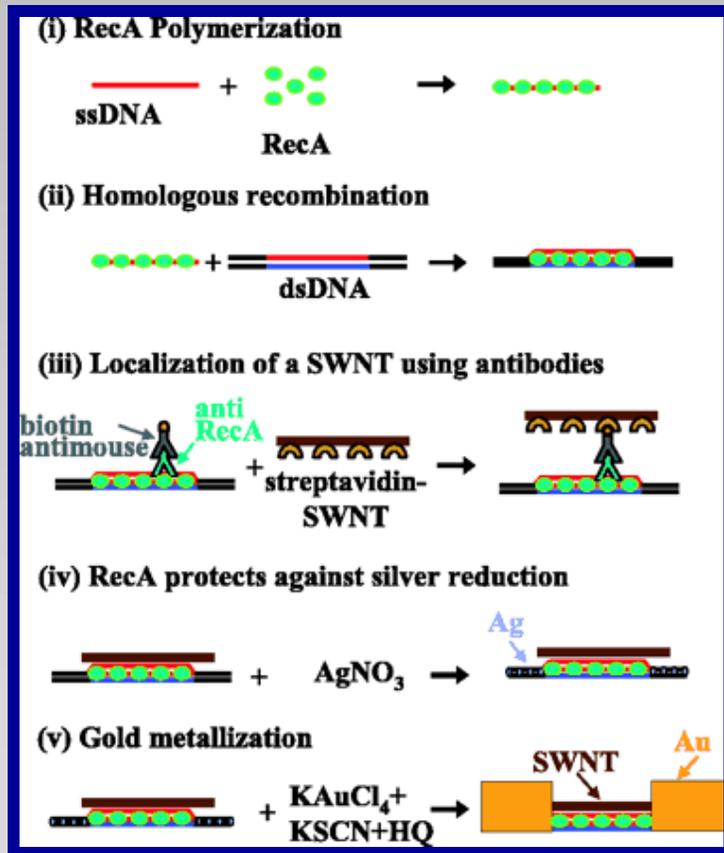
Promise of high-density,  
compact,  
sophisticated systems



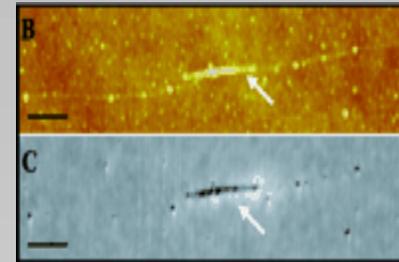
Challenges: Complexity

- scale-up: accurate assembly
- controlling/predicting diverse interactions
- integration of diverse materials

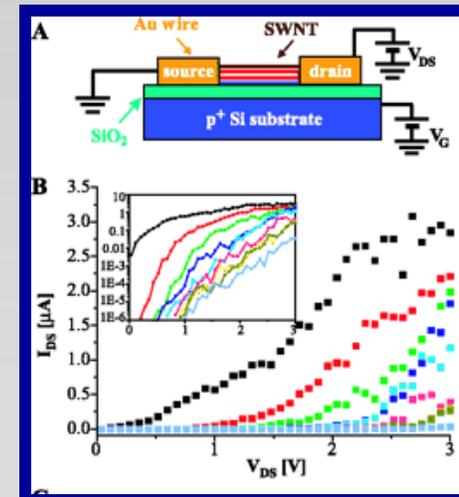
# Linking Nanoscale Building Blocks: integrating assembly motifs



'DNA-Templated Carbon Nanotube Field-Effect Transistor', Keren et al., Science 302, 1380 (2003)

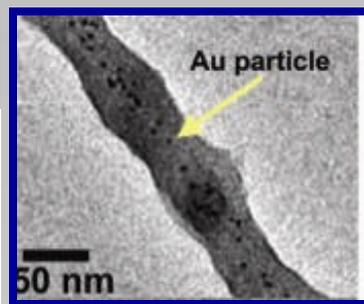
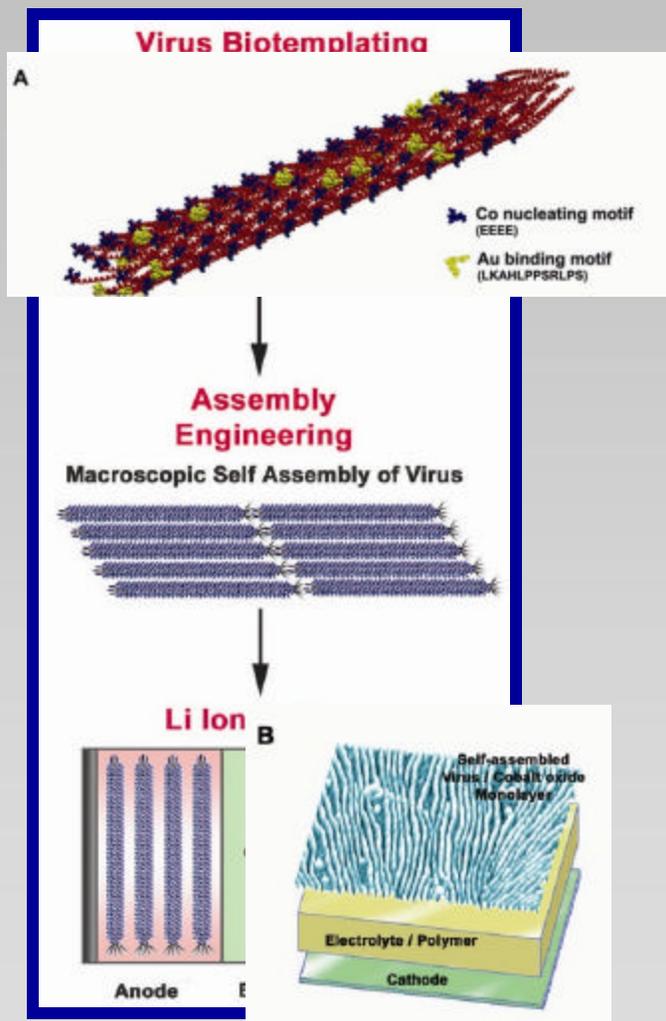


Carbon nanotube placed at specific site on DNA scaffold  
[b] AFM, [c] scanning conductance measurement



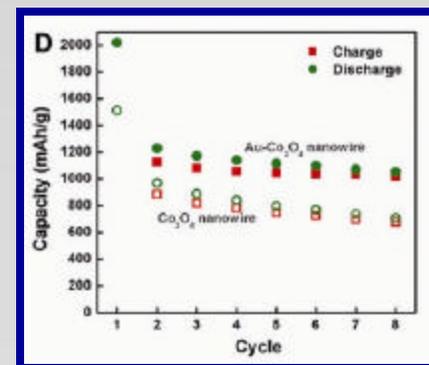
Transistor characteristics

# Using Protein Templates to Form Batteries



Based on material selection through phage display libraries

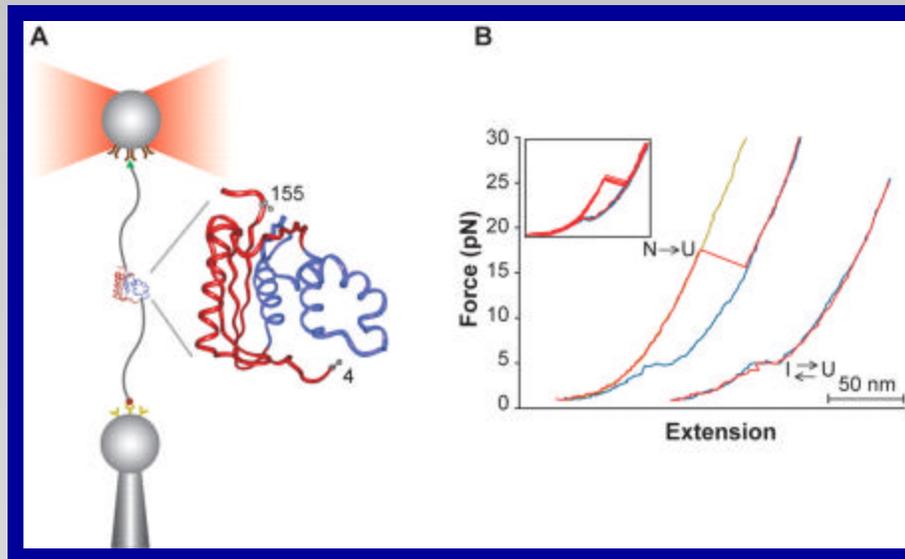
- Hybrid materials to optimize performance
- Ordering at the nanoscale using biological template
- Low temperature, efficient formation of battery, and...
- Improved battery characteristics (capacity)



Nam et al., *Science Express*, Apr. 2006

# Probing, pinching, utilizing biological conformations

'Direct Observation of the Three-State Folding of a Single Protein Molecule', Cecconi et al.,  
Science 309, 2057 (2005)



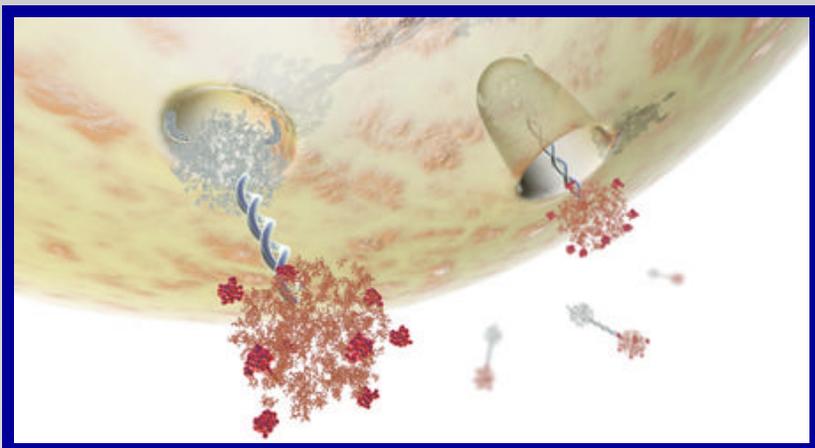
Probe folding of RNase H through

- selective tethering to polystyrene spheres
- use of optical tweezers to stretch & release

# New Opportunities in 'Nanomedicine'



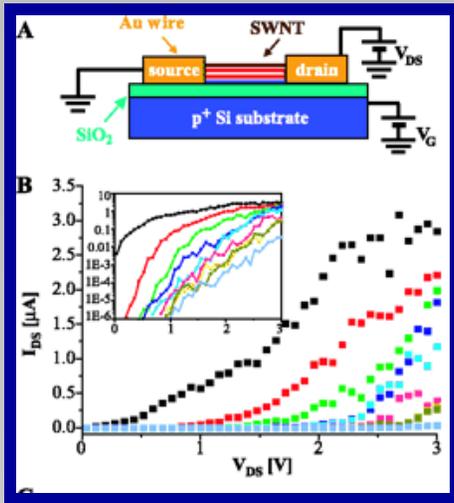
Technology Review March/April 2006  
'Ten Emerging Technologies'



Targeted drug delivery to cancer cells  
James Baker, University of Michigan

## Nanomedicine:

- Medical intervention at the molecular scale for curing disease, repairing damaged tissues
- Building "nano" structures or "nano" machines that are compatible with living tissues and can safely operate inside the body.
- Providing better diagnostic tools



New approaches to synthesis & assembly of electronic, optical devices

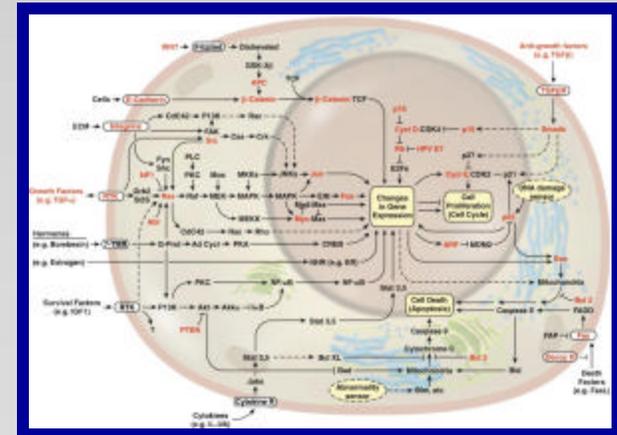
- templating at nanoscale
- molecular recognition strategies
- analogues for information processing



Systems-level issues:  
New energy/power sources

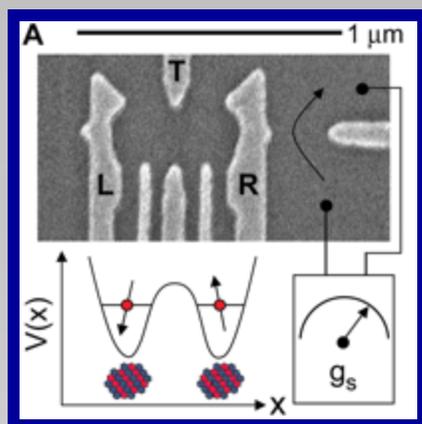
Challenges: 'Translation'

- going beyond simple analogues
- understanding large-scale assembly & interactions
- understanding 'context'

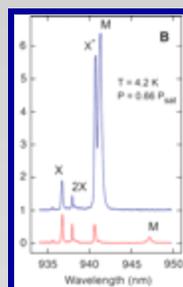
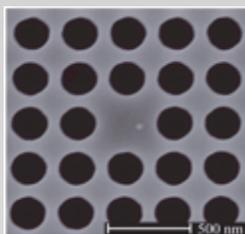


'The Emergent Integrated Circuit of the Cell'  
Hanahan & Weinberg, Cell [2000]

# Control & Coherence: new means of information processing

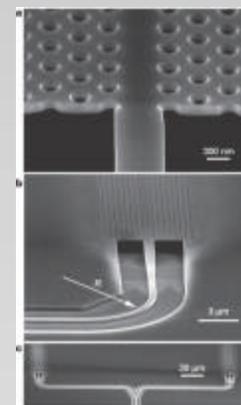
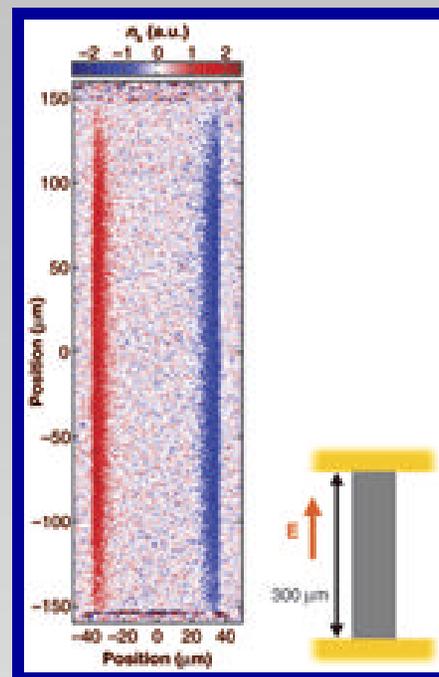


'Coherent Manipulation of Coupled Electron Spins in Semiconductor Quantum Dots', Petta et al., Science 309, 2180 (2005)



'Deterministic Coupling of Single Quantum Dots to Single Nanocavity Modes', Badolato et al., Science 308, 1158 [2004]

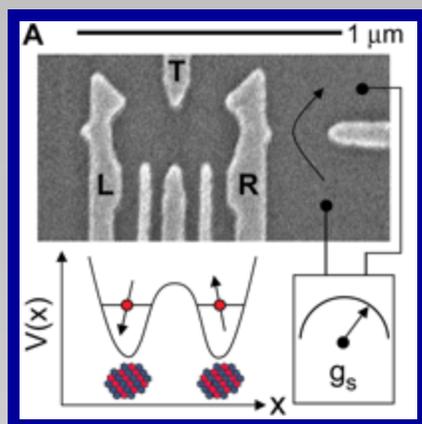
'Observation of the Spin Hall Effect in Semiconductors', Kato et al., Science 306, 1910 [2004]



'Active control of slow light on a chip with photonic crystal waveguides', Vlasov et al., Nature 438, 65 [2005]

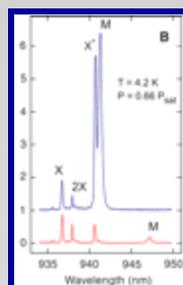
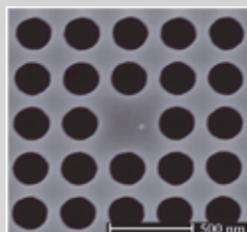
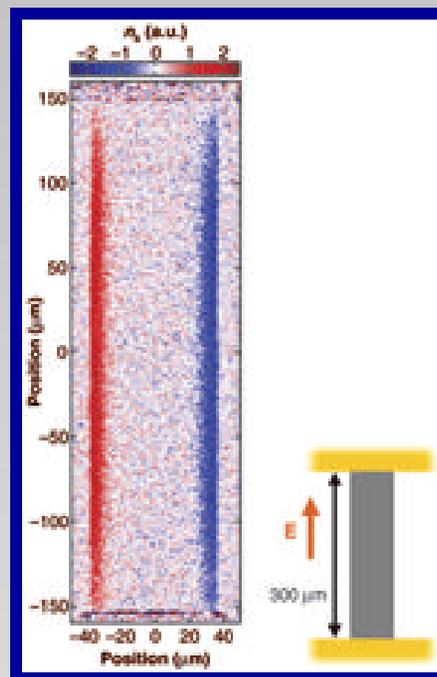
Promise: manipulating coherent populations of electrons, photons, spin

# Control & Coherence: new means of information processing

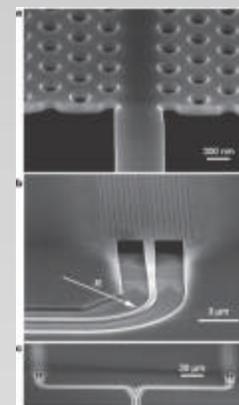


'Coherent Manipulation of Coupled Electron Spins in Semiconductor Quantum Dots', Petta et al., Science 309, 2180 (2005)

'Observation of the Spin Hall Effect in Semiconductors', Kato et al., Science 306, 1910 [2004]



'Deterministic Coupling of Single Quantum Dots to Single Nanocavity Modes', Badolato et al., Science 308, 1158 [2004]



'Active control of slow light on a chip with photonic crystal waveguides', Vlasov et al., Nature 438, 65 [2005]

Challenge: how far can we extend/scale coherent systems? Under what conditions?

# Accessing the Frontiers of Nanotechnology

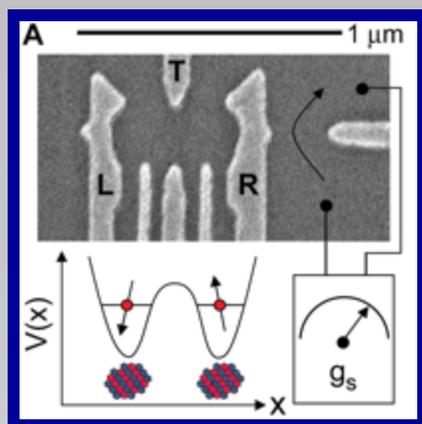
Tremendous Achievements in Integrating Building Blocks of Materials & Techniques

- Research at the atomic, molecular or macromolecular scale (1-100nm)
- Utilizing novel properties of materials at the nanometer scale
- Imaging, measuring, modeling, and manipulating matter at this length scale.

Challenges:

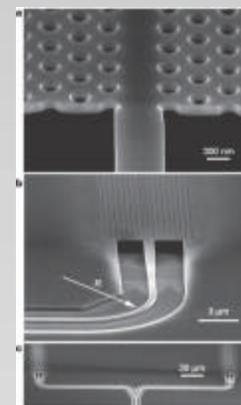
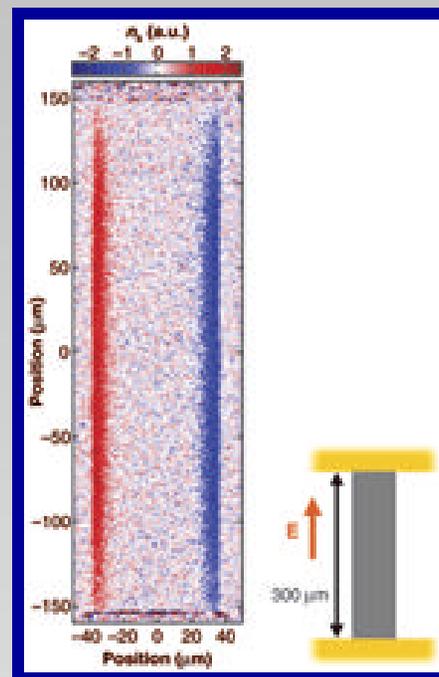
- Complexity
  - scaling up to large systems
  - integration of diverse materials
  - controlling diverse interactions
  - predicting emergent properties
- Translation: across disciplines
  - going beyond simple analogues
  - understanding 'context'

# Control & Coherence: new means of information processing

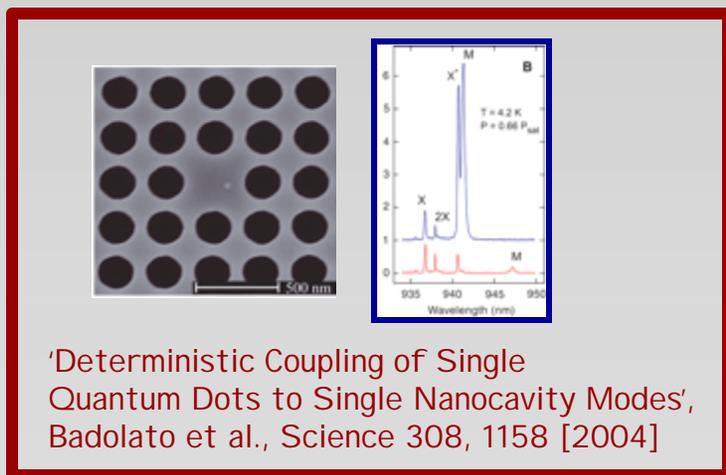


'Coherent Manipulation of Coupled Electron Spins in Semiconductor Quantum Dots', Petta et al., Science 309, 2180 (2005)

'Observation of the Spin Hall Effect in Semiconductors', Kato et al., Science 306, 1910 [2004]



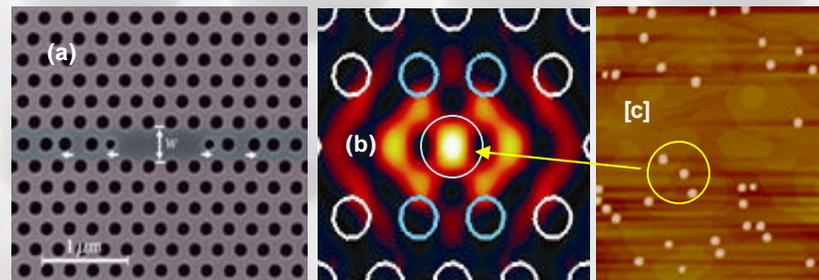
'Active control of slow light on a chip with photonic crystal waveguides', Vlasov et al., Nature 438, 65 [2005]



'Deterministic Coupling of Single Quantum Dots to Single Nanocavity Modes', Badolato et al., Science 308, 1158 [2004]

Challenge: how far can we extend/scale coherent systems? Under what conditions?

## 'Coupled quantum dot-photonic crystal cavities'



### Tuning the Optical Environment at the Nanoscale

Evelyn Hu, Kevin Hennessy, Stefan Strauf,  
M. T. Rakher, Pierre M. Petroff, Dirk Bouwmeester  
University of California at Santa Barbara

Antonio Badolato, M. Atatüre, Atac Imamoglu  
ETH-Zurich

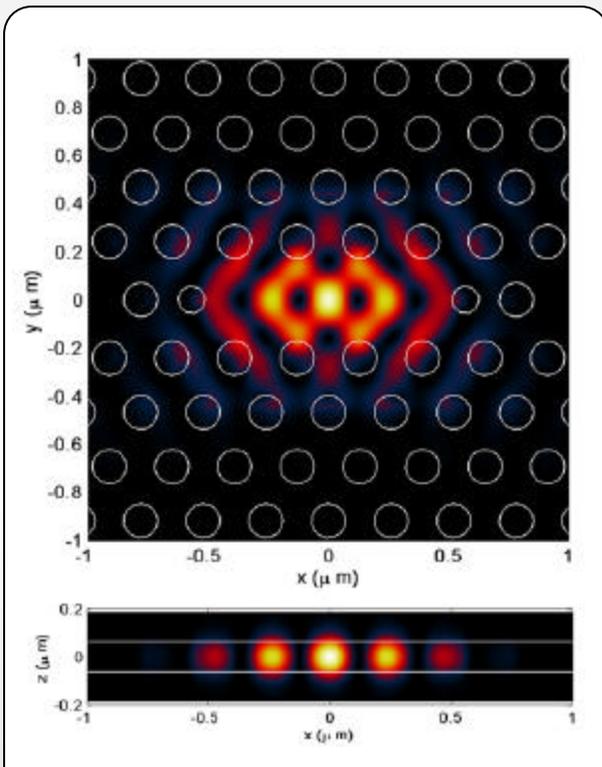


# Quantum dots (QDs) in photonic crystals (PCs)

Photon confinement

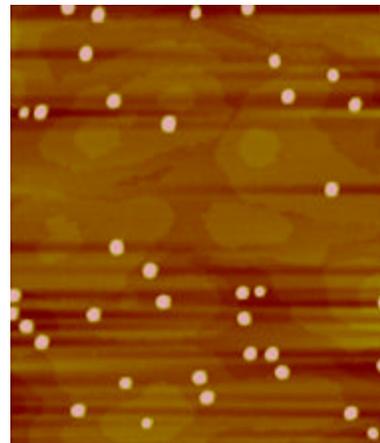
Electron confinement

Cavity-QED



Photonic crystal cavity

High  $Q$ , small modal volumes

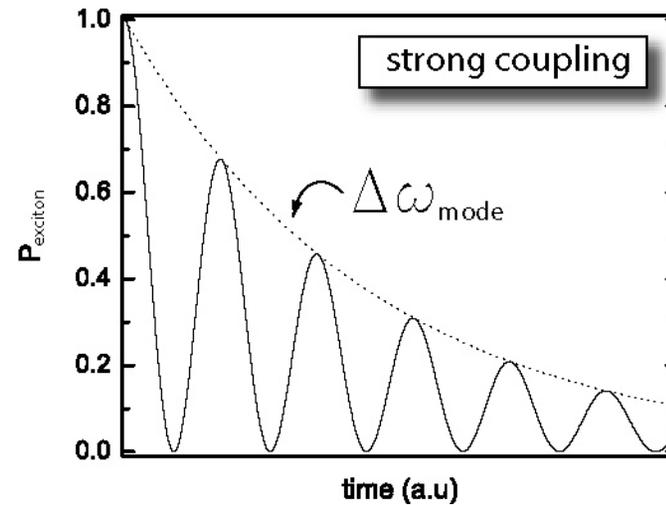
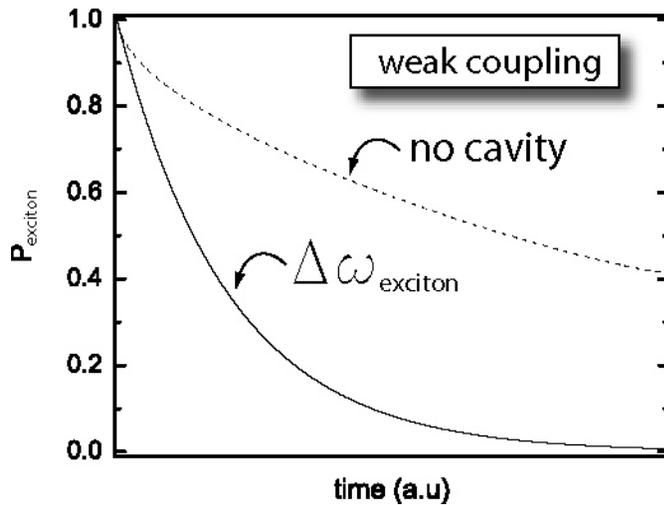
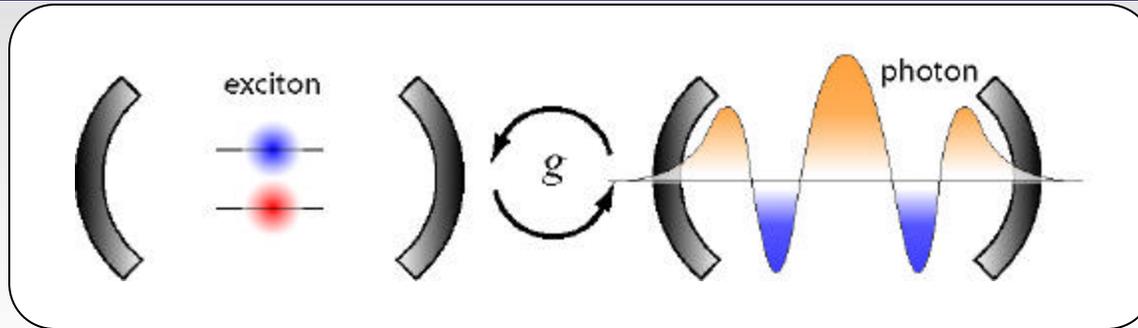


InAs self-assembled quantum dots

'atom-like' spectra  
sharp excitonic transitions

- single photon sources
- entangled photon pair generation

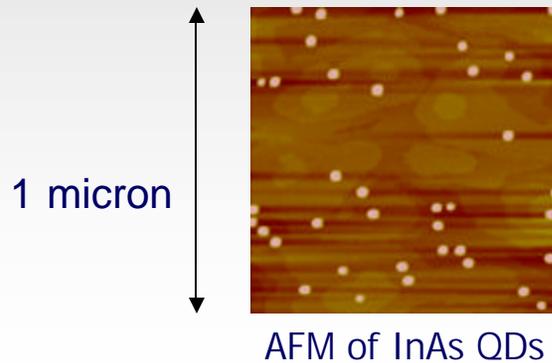
# Exciton/cavity-mode coupling



- Purcell effect
- single photon sources
- entangled photons

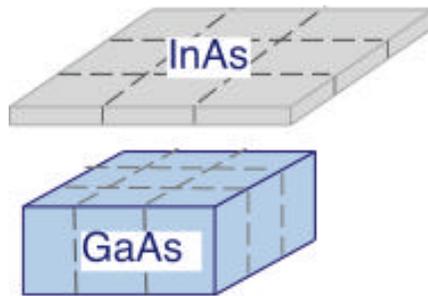
- entangled exciton/photon states
- single photon sources
- quantum gate operations

# Semiconductor Quantum Dots

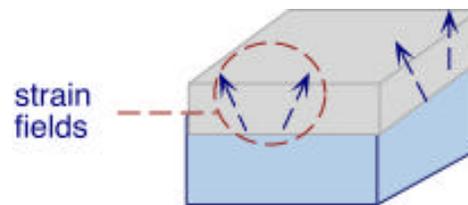


Single-crystal semiconductors  
Dimensions small enough to detect  
discrete energy levels ( $\Delta E > kT$ )

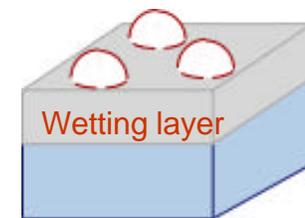
- InAs quantum dots formed through strain-mediated Molecular Beam Epitaxy
- ~ 30 nm diameter, ~ 10% dispersion in size
- **Low QD density** ~  $10^9/\text{cm}^2$  (~ 10 QDs/ $\mu\text{m}^2$ )



Lattice-mismatched  
materials

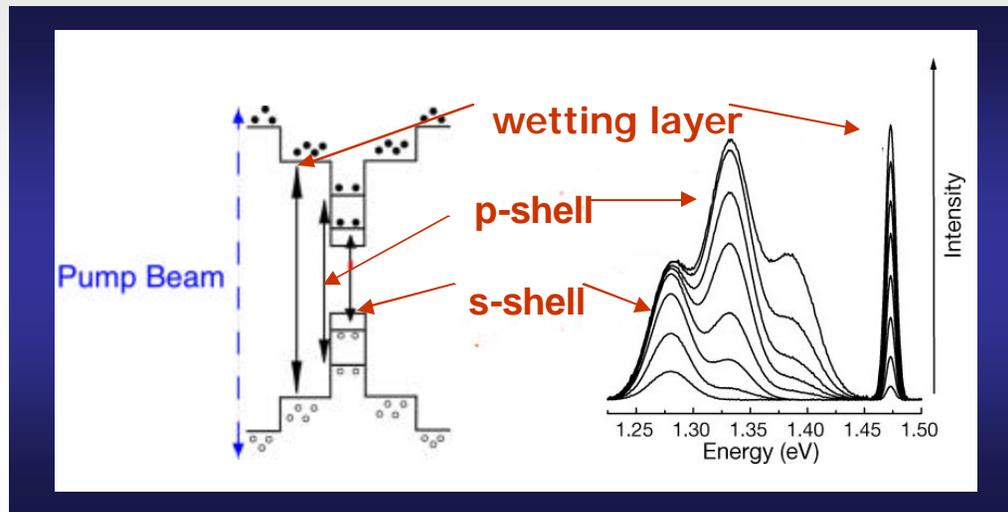


Strained-layer epitaxy  
(Stranski-Krastonow)



Carefully form quantum dot  
structures

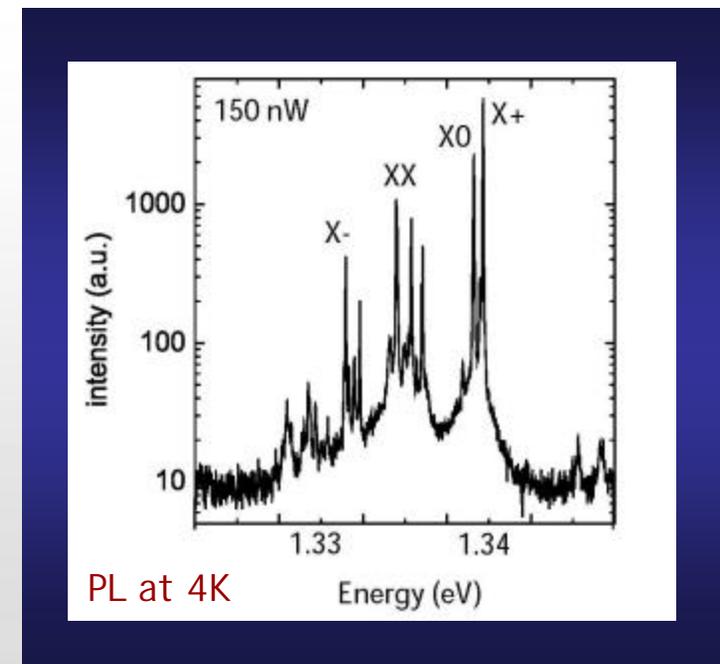
# Semiconductor Quantum Dots: optical signature



Broad luminescence peaks reflect distribution of QD size

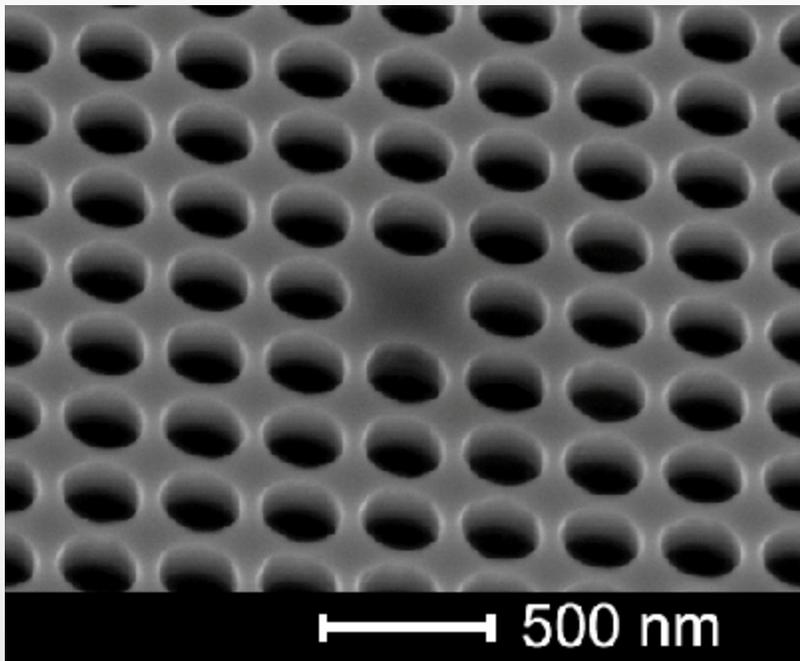
Narrow linewidths ( $\sim$  few  $\mu\text{eV}$ ) for single QDs  
Discrete excitonic transitions observed

'high optical efficiency emitters, narrow linewidths'



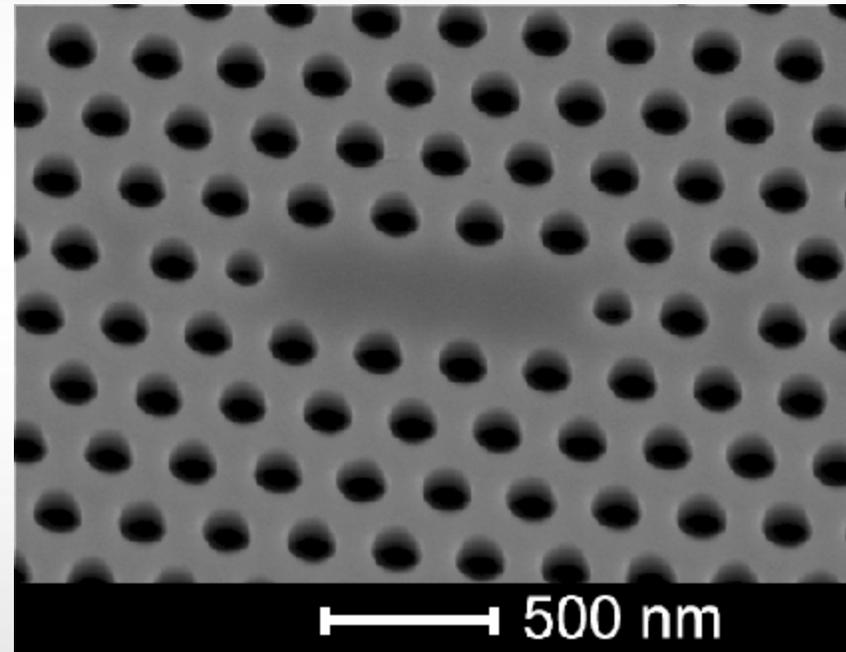
## 'High Q, small volume cavities'

Photonic crystals selected as optical cavities since they can support modes of ultra-small volume and high ( $> 1000$ ) quality factor ( $Q$ )



S1

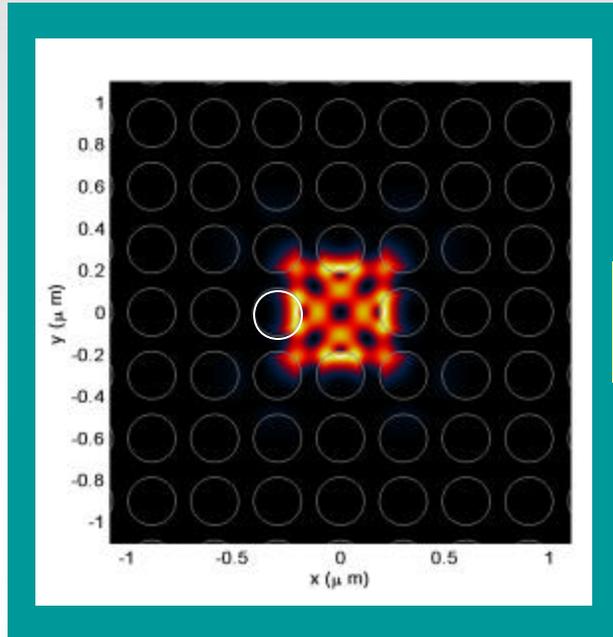
(gallium arsenide, GaAs)



L3

# Tuning the Theoretical Q

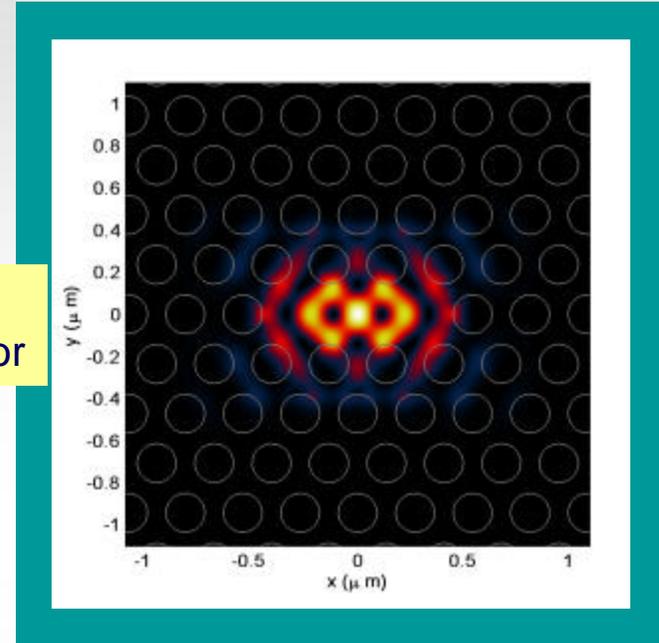
S1



$$V_{\text{eff}} = 0.74 (\lambda/n)^3$$

$$n_{\text{eff}} = 2.55$$

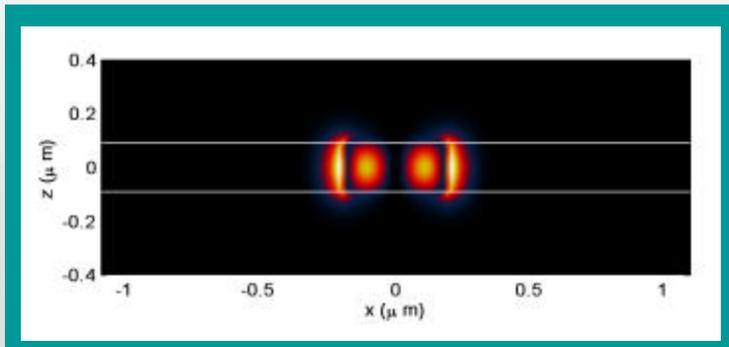
L3



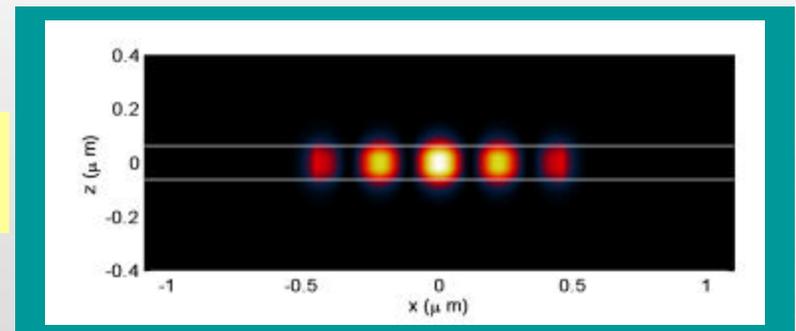
$$V_{\text{eff}} = 0.70 (\lambda/n)^3$$

$$n_{\text{eff}} = 2.71$$

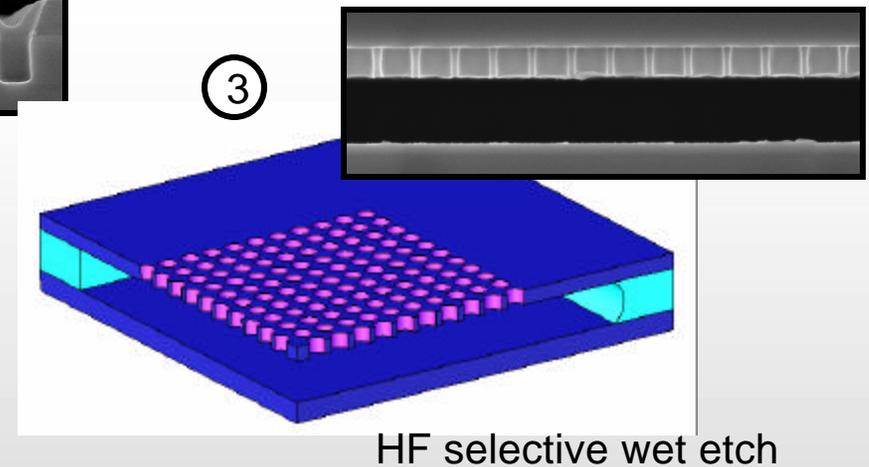
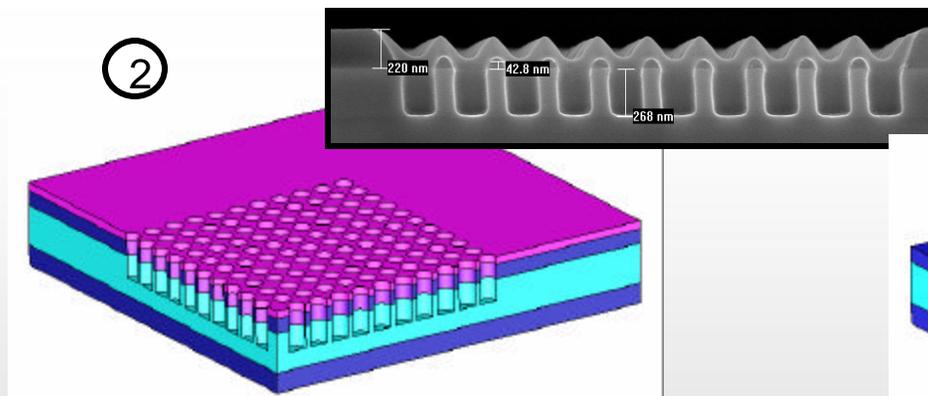
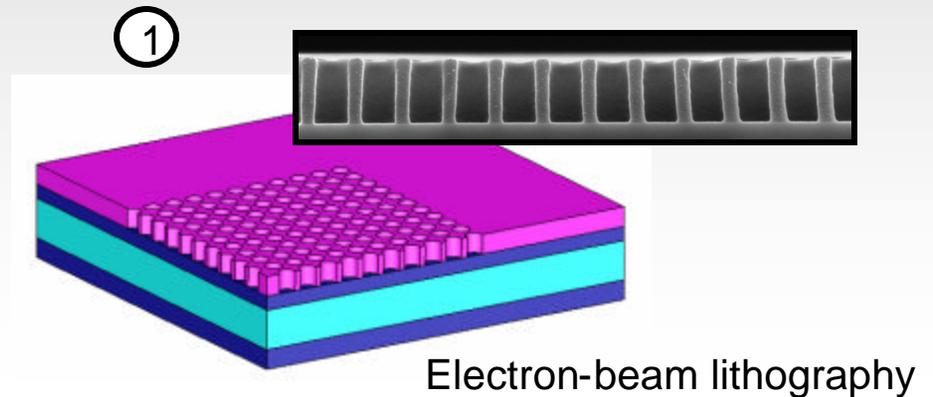
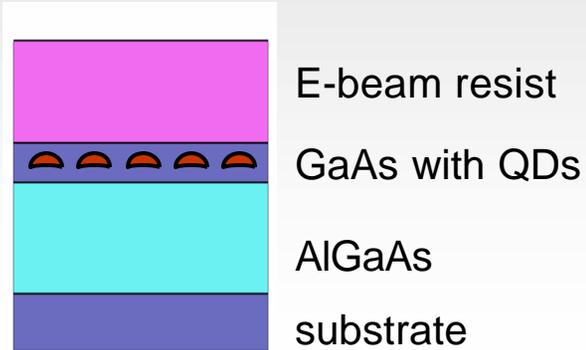
Mode maximum  
within semiconductor



Minimize  
vertical loss

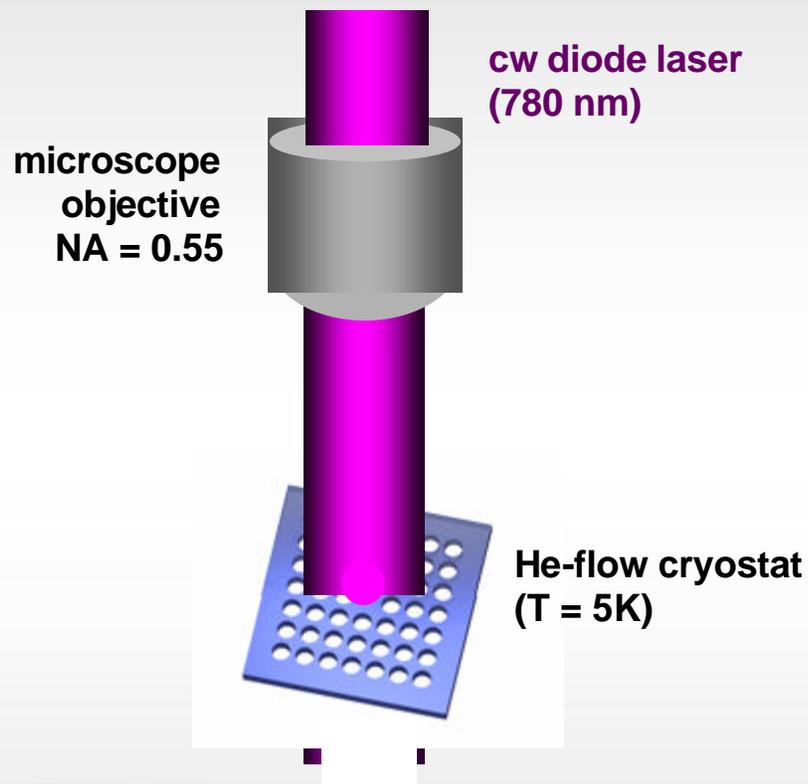


# Fabrication of Photonic Crystal Membranes



In-plane confinement, photonic crystal  
Out-of-plane confinement: variation of index of refraction

# What signatures do we hope to find?



Photoluminescence (PL) using diode laser (780 nm) focused on the defect

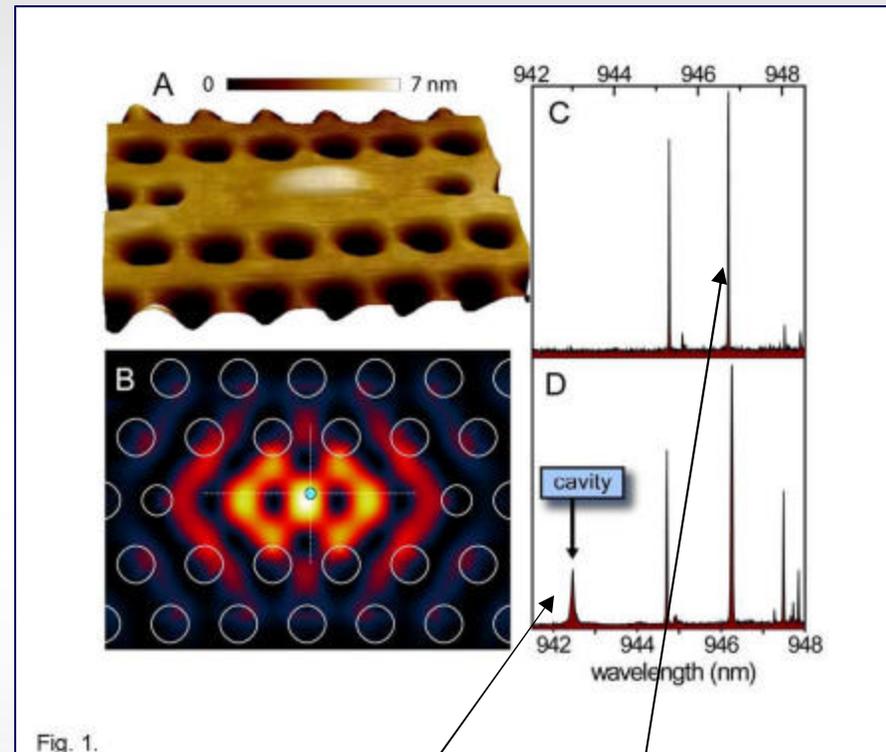


Fig. 1.

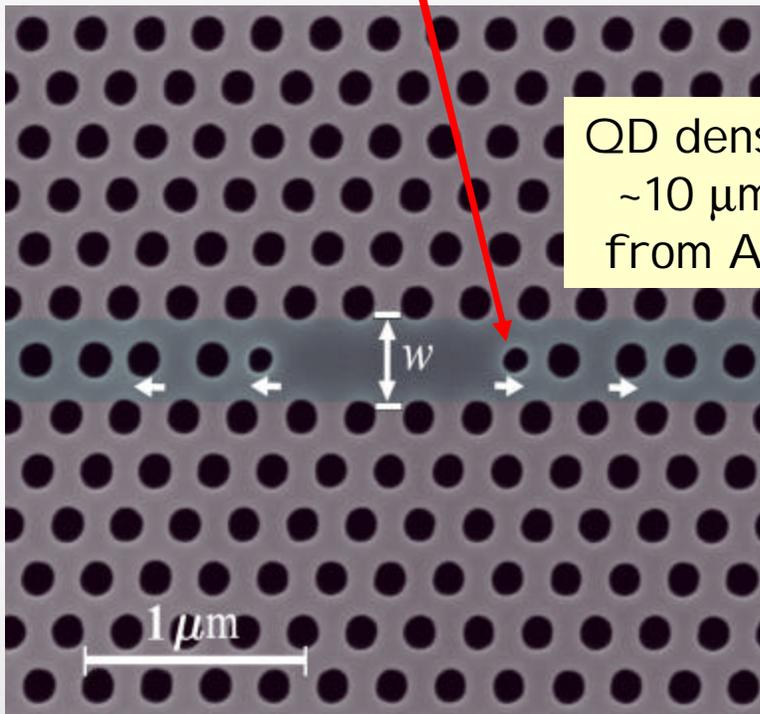
- Discrete QD exciton transitions
- High Q cavity transition
- Spatial resonance
- Spectral resonance

# Light Amplification from Randomly Positioned QDs

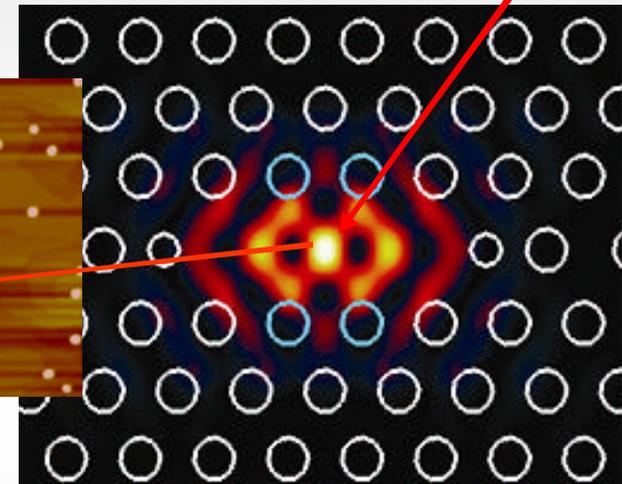
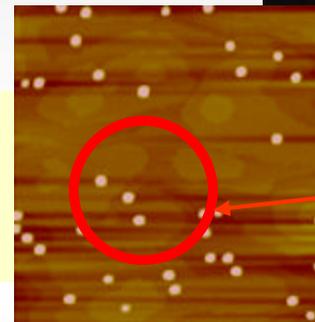
Size and position optimized for high Q and high  $n_{\text{eff}}$

Modified L3 cavity

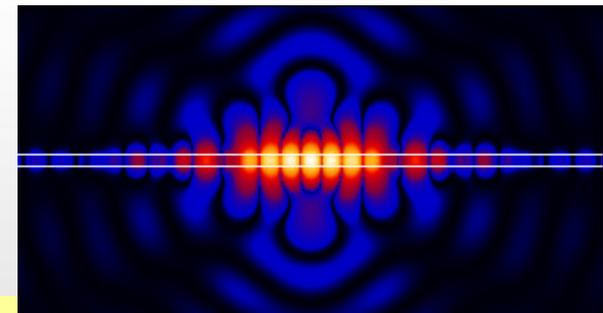
Field stays away from interface



QD density  $\sim 10 \mu\text{m}^{-2}$  from AFM



Side View

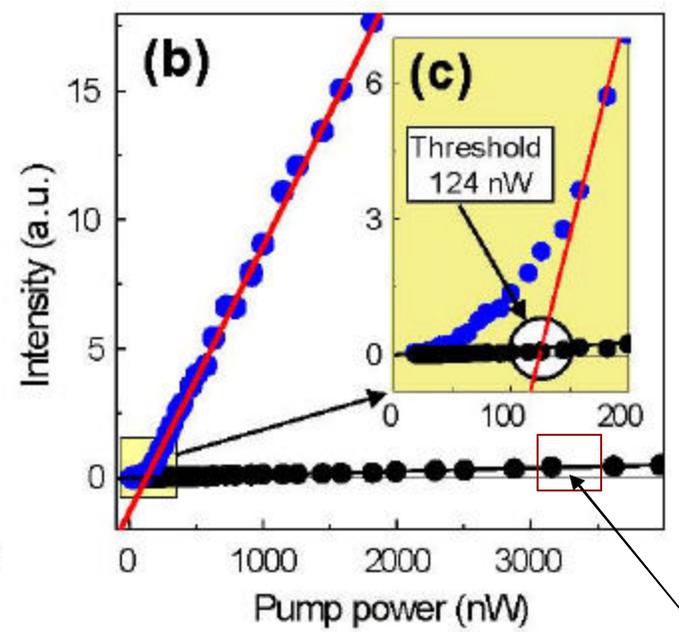
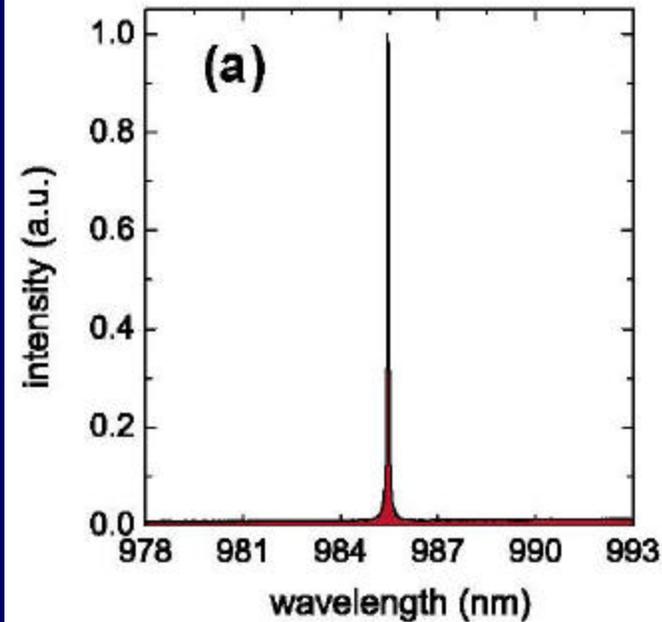


Strauf et al.,  
*Phys. Rev. Lett.* **96**,  
127404/1-4 [2006]

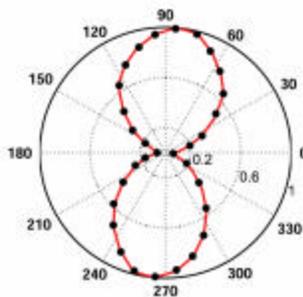
Quality factor  
Mode volume  
Effective index

$Q \sim 18000$   
 $V \sim 0.68(\lambda/n)^3$   
 $n_{\text{eff}} \sim 2.9$

# Exceptional lasing performance



Spontaneous emission background

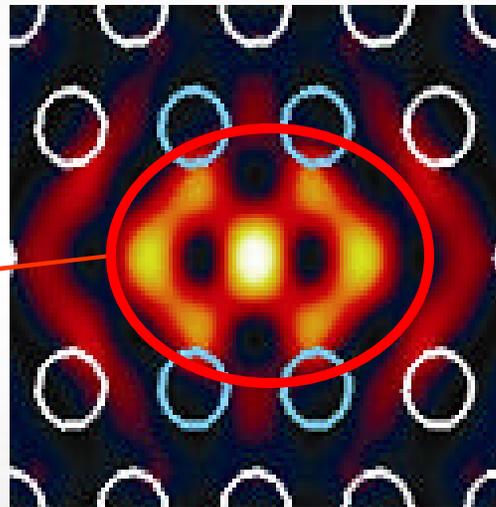
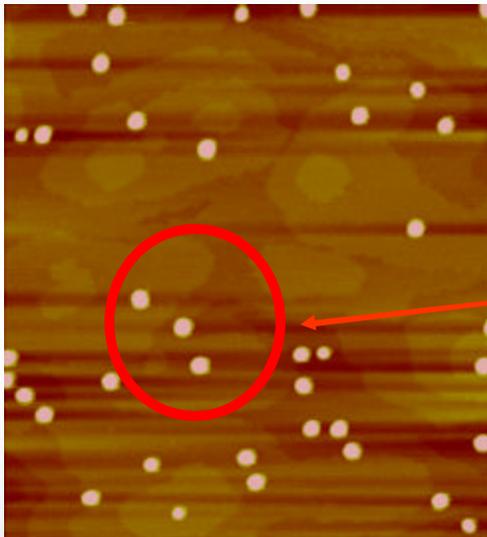


Lasing observed with low thresholds in ~ 80% of all samples tested

# Low density of QDs as gain medium

QD density  
 $5\text{-}50 \mu\text{m}^{-2}$   
from AFM

Mode volume  
from FDTD



QDs are spectrally  
distributed over 50-100 nm

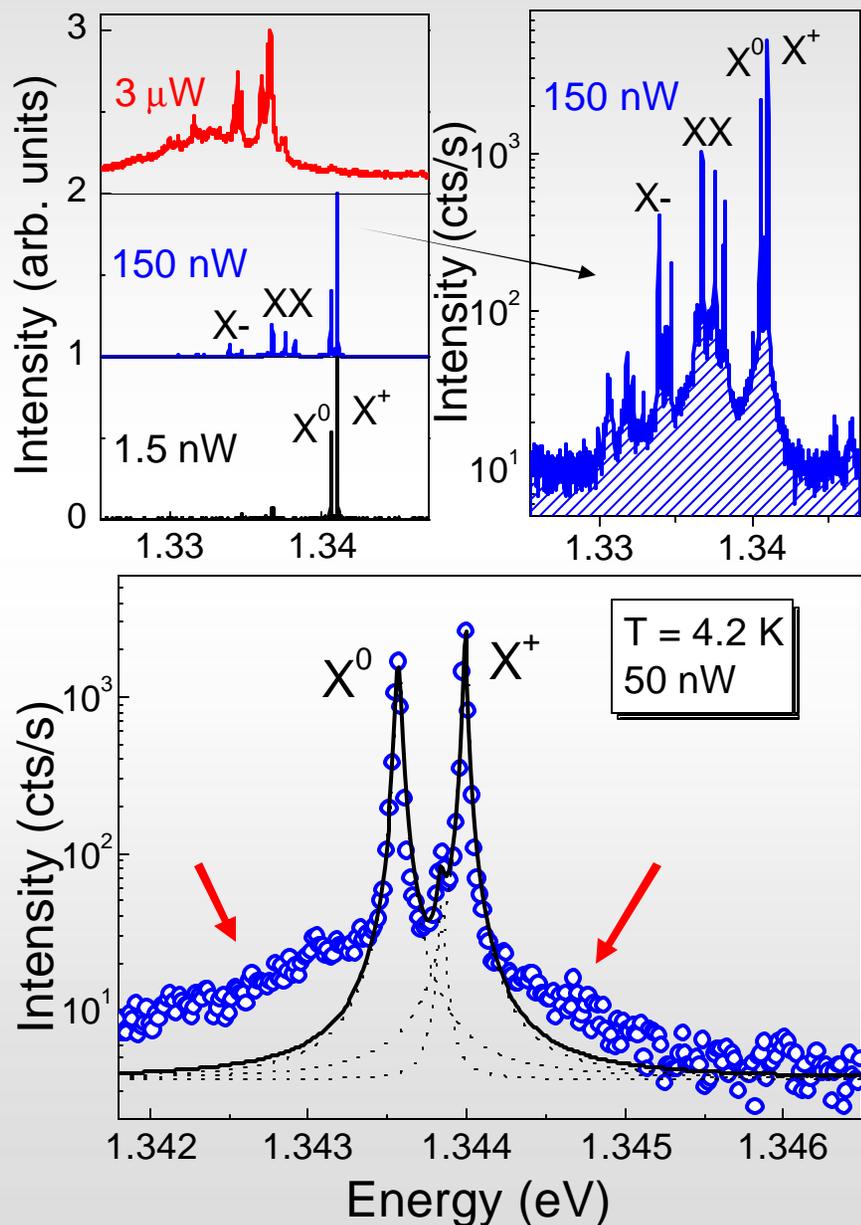
Sharp exciton resonance

Chance of  $\sim 1\%$  for both  
spatial and spectral coupling

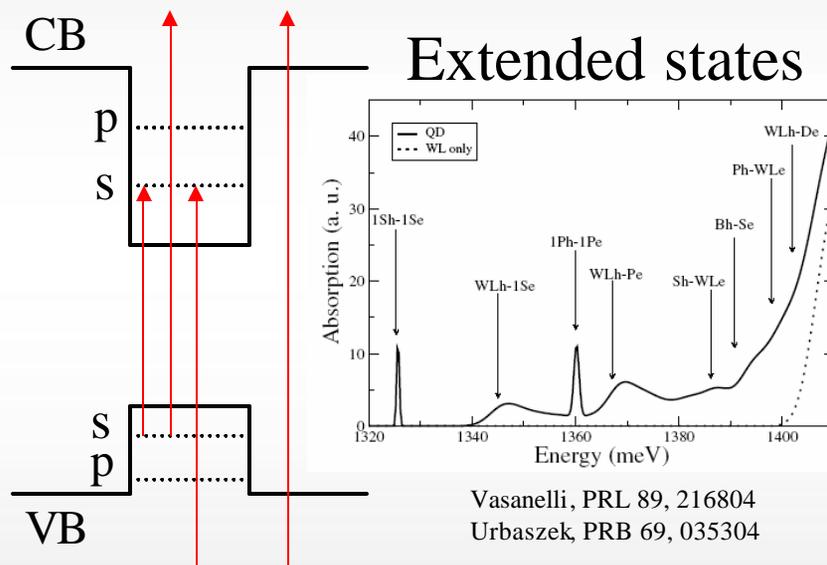
Only **1-3 QDs** are  
within the mode !

No pronounced coupling  
is expected:  
What is the mechanism  
of lasing?

# Single QDs are broadband emitters (?)



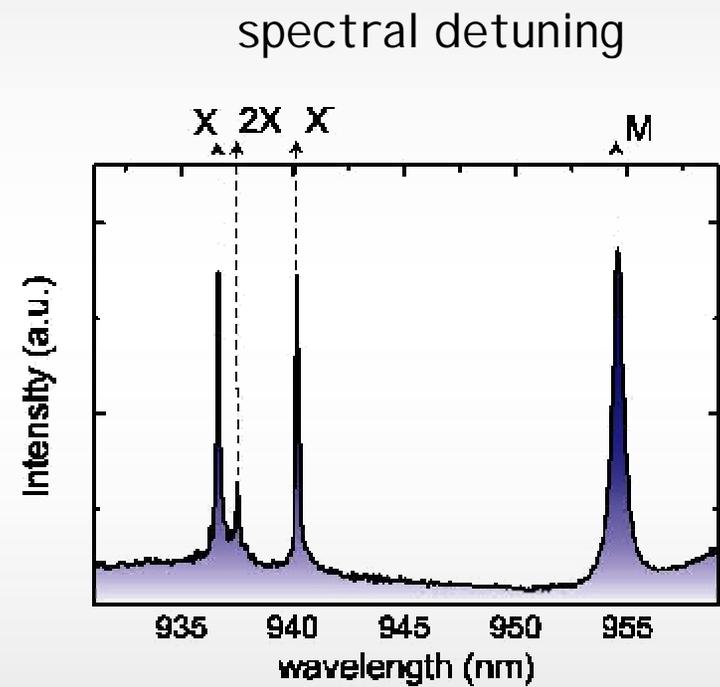
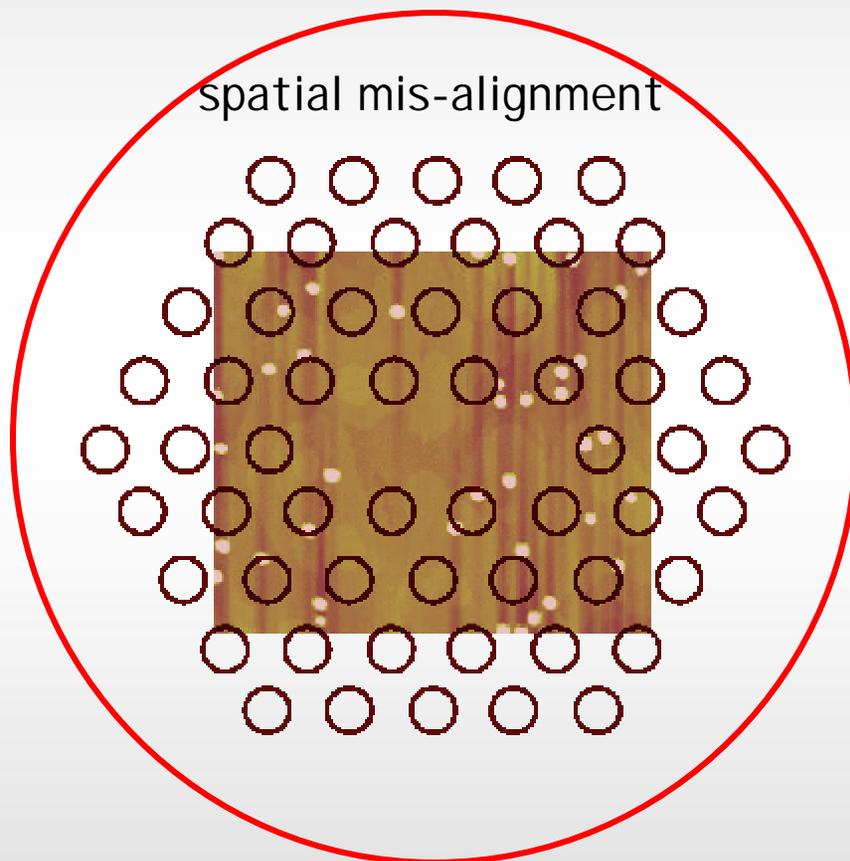
- charged states  $X^+$ ,  $X^0$ ,  $X^-$  (Warburton, Nature 405, 926)
- bi- and multi Xs (Moreau, PRL 87, 183601)



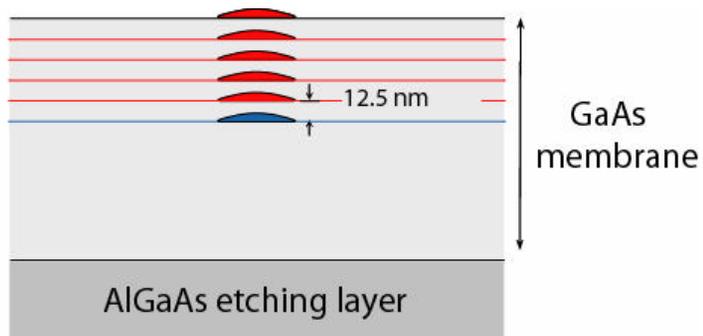
- acoustic phonon coupling (Muljarov, PRL 93, 237401)

QD interaction with surrounding matrix provides **indirect** but **robust** coupling

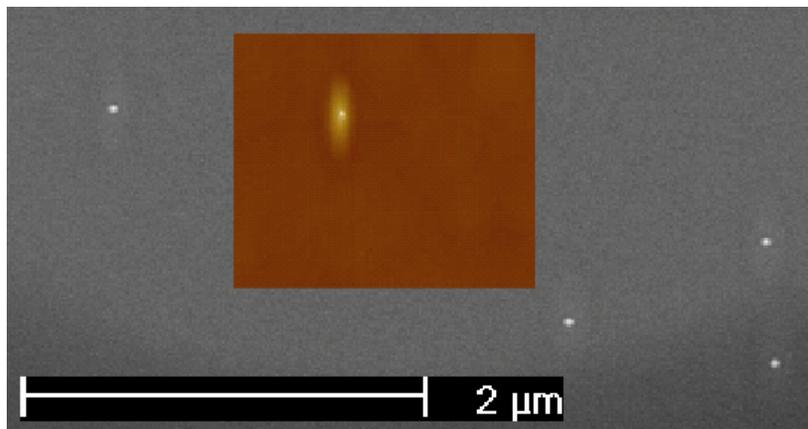
# Achieving Spatial and Spectral Resonance



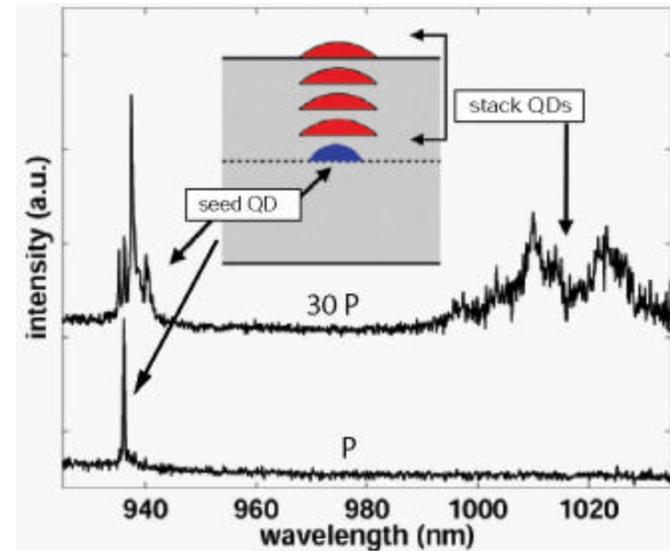
# Spatial alignment: *Active Positioning*



Vertically stacked quantum dots  
grown by Antonio Badolato

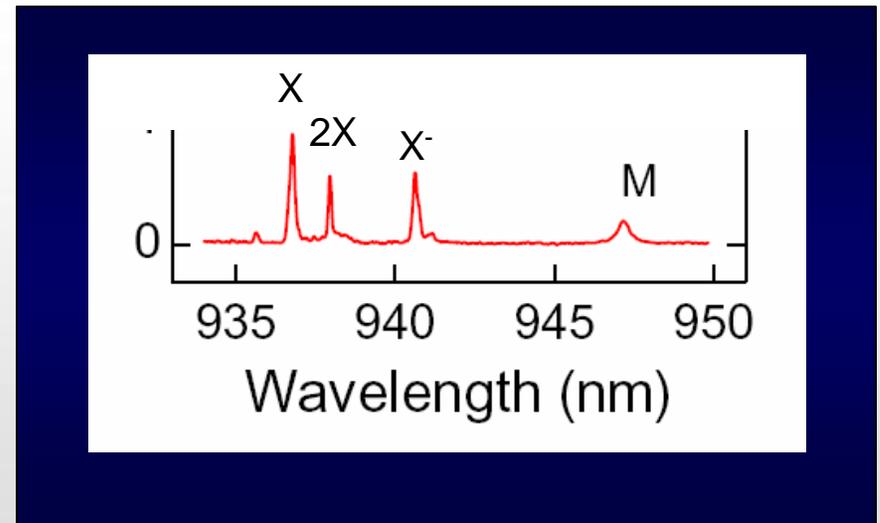
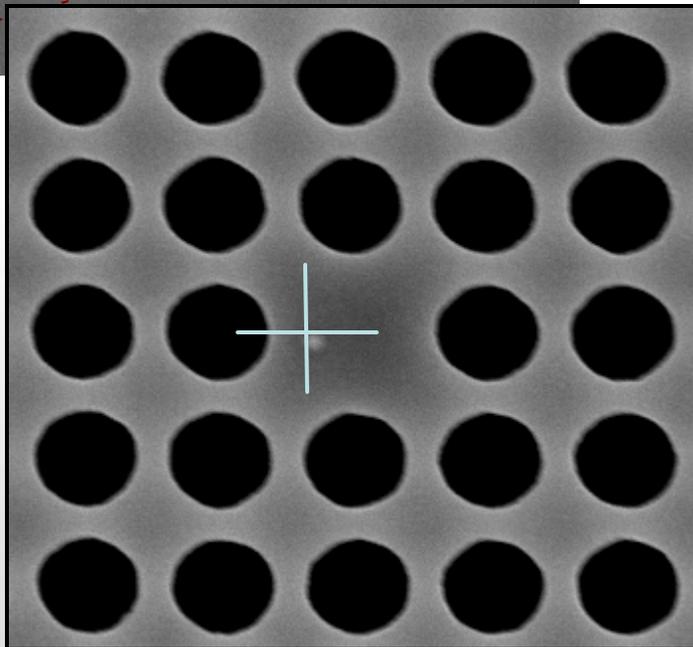
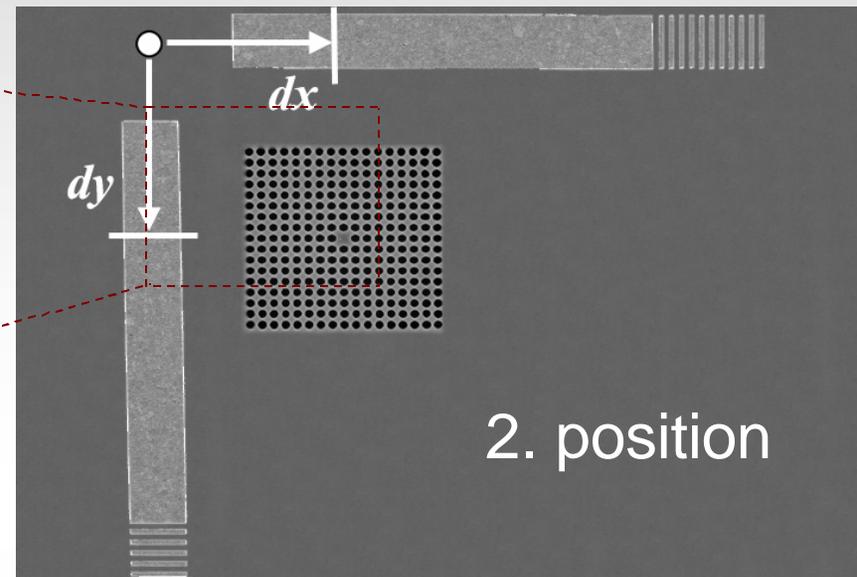
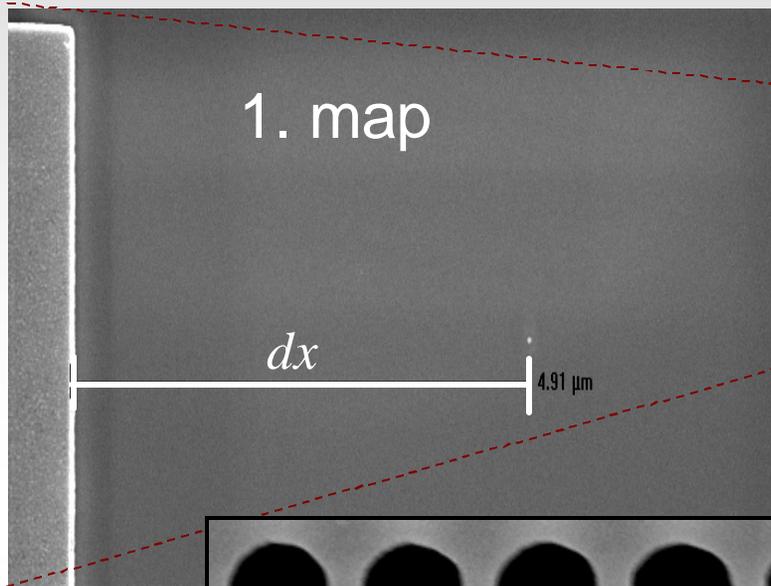


SEM of several stacks (AFM inset)



- use stack of QDs as a tracer
- SEM to “see” the stack, map relative to alignment marks
- Fabricate cavity by e-beam lithography around stack

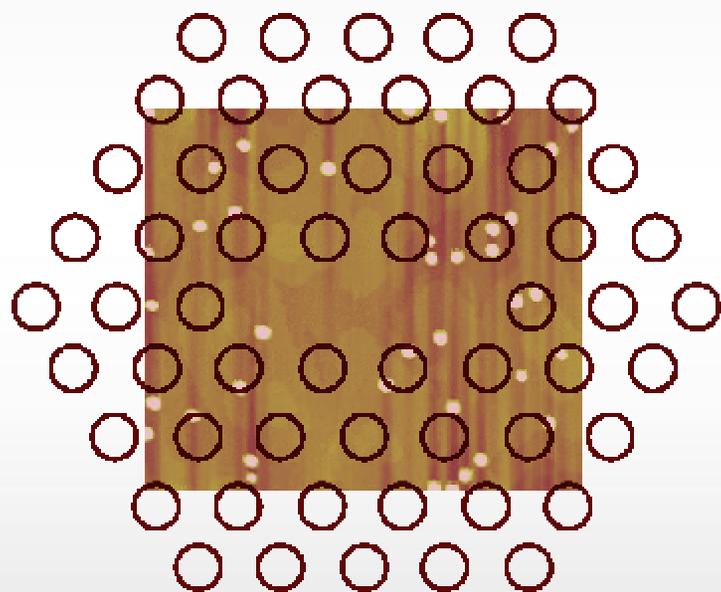
# Spatial alignment: *Active Positioning*



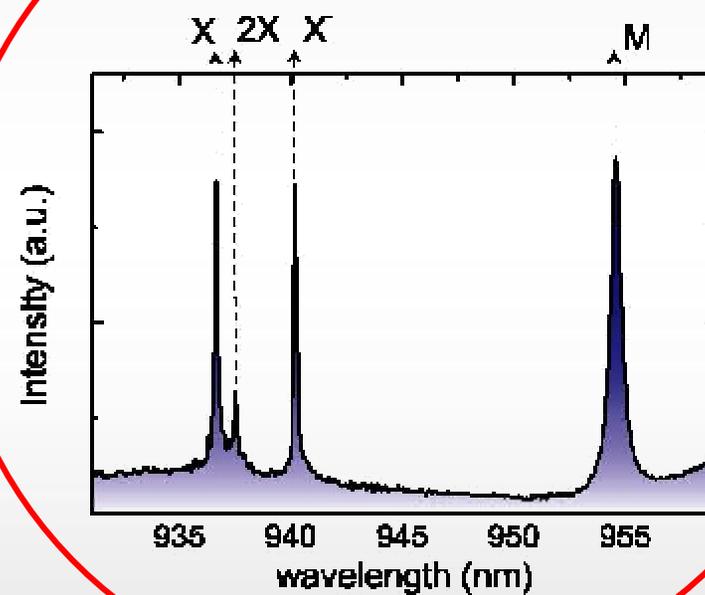
Resonance not exactly achieved

# Achieving Spatial and Spectral Resonance

spatial mis-alignment



spectral detuning



# Spectral coupling: *digital etching*

Can we tune the mode after initial processing?

wet chemical digital etching to thin membrane

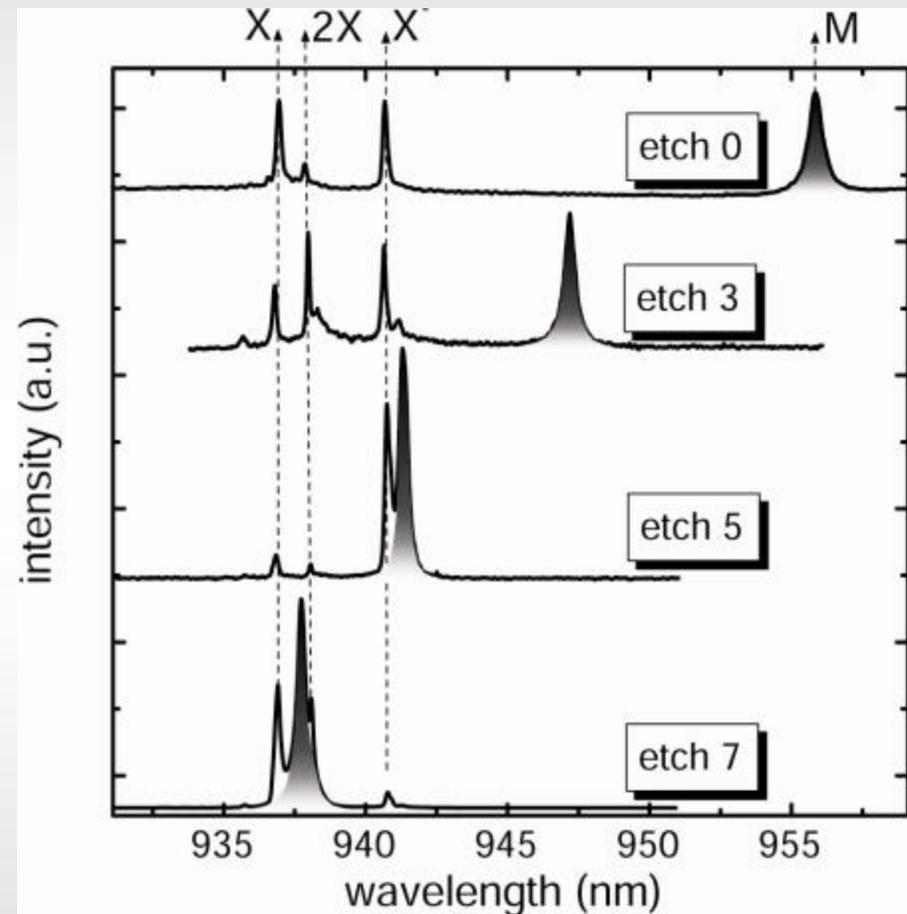
PC slab (side view)



form ultra-thin native oxide

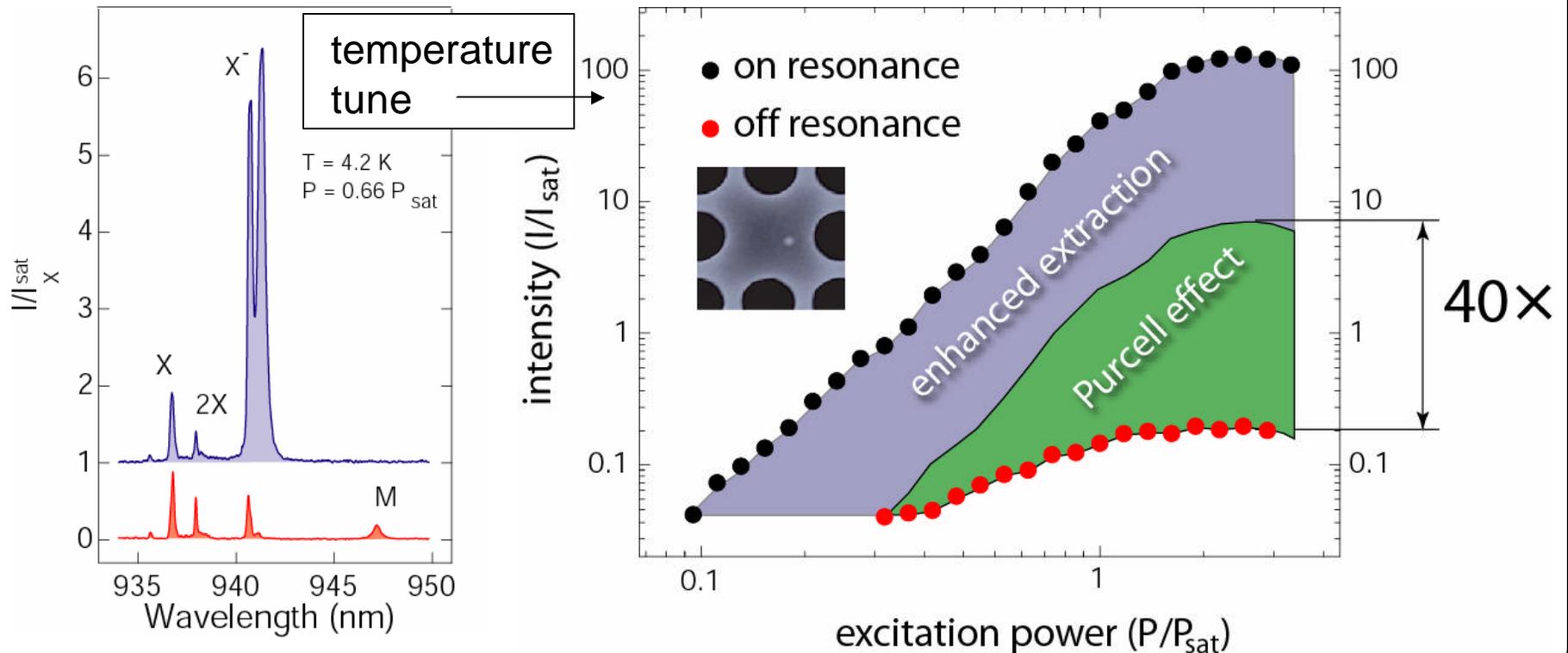


remove oxide in acid



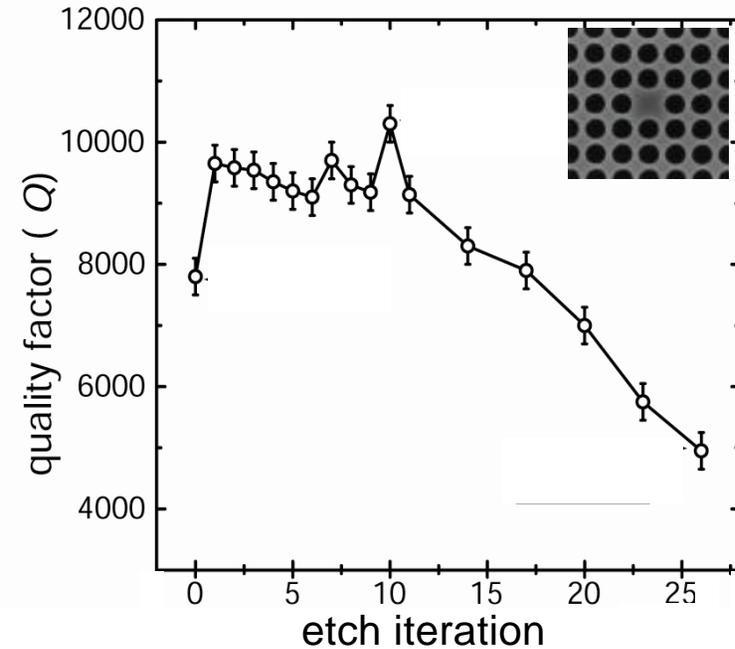
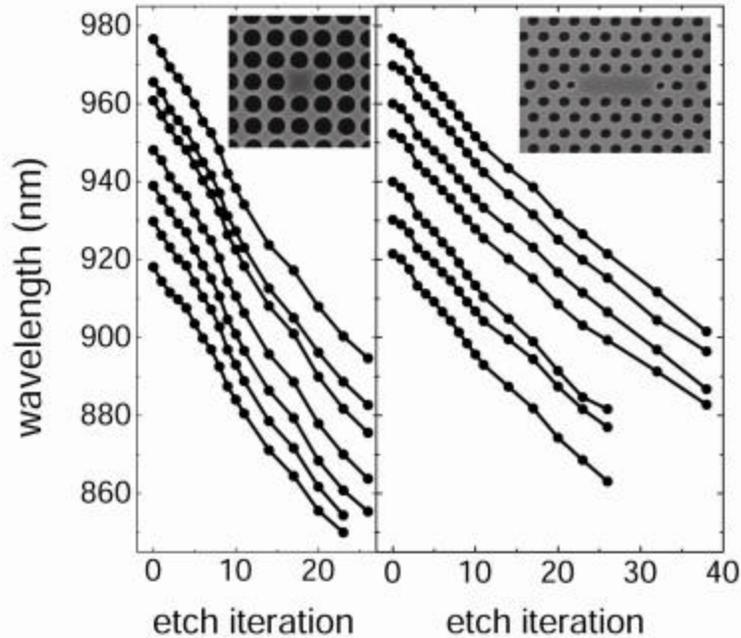
# Exciton/mode coupling results

Science **308**, 1158 (2005)



- **700 times intensity enhancement on resonance!**
- exciton lifetime beyond resolution on/near resonance
- estimated Purcell factor of 40

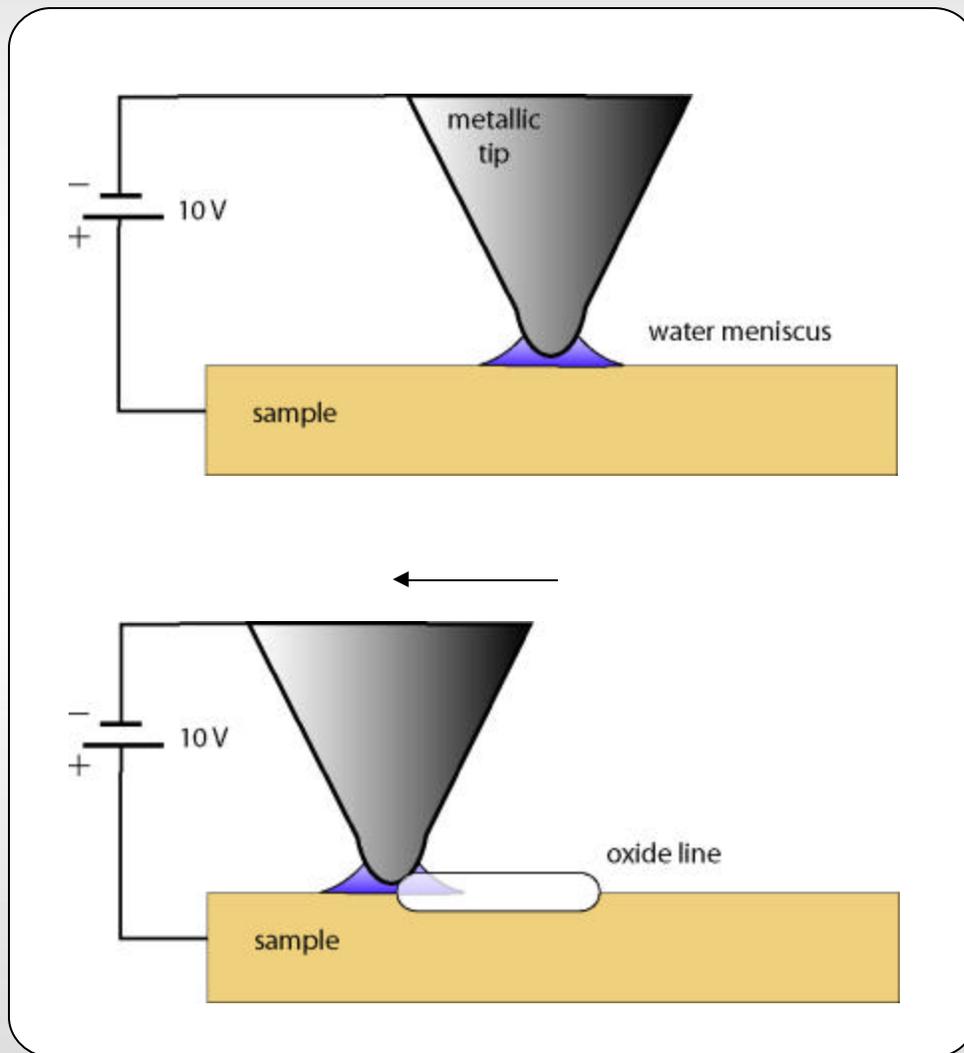
# Precise & wide tuning by digital etching



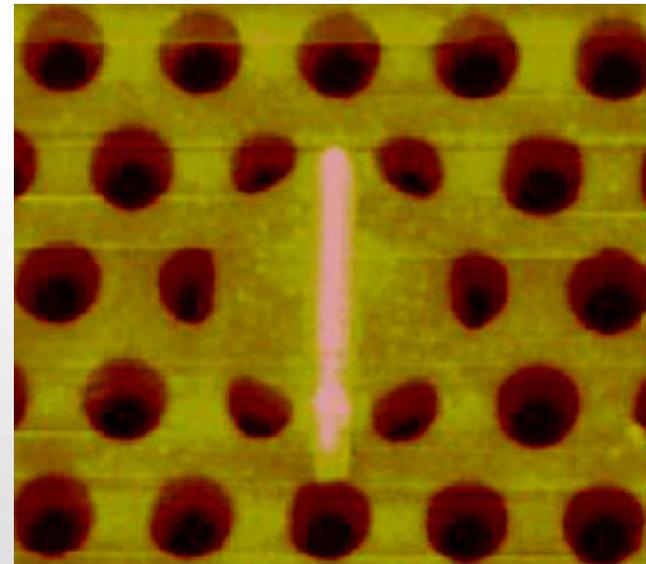
- 2-3 nm/cycle over 80 nm
- High Q over long range

Appl. Phys. Lett. **87**, 021108 (2005)

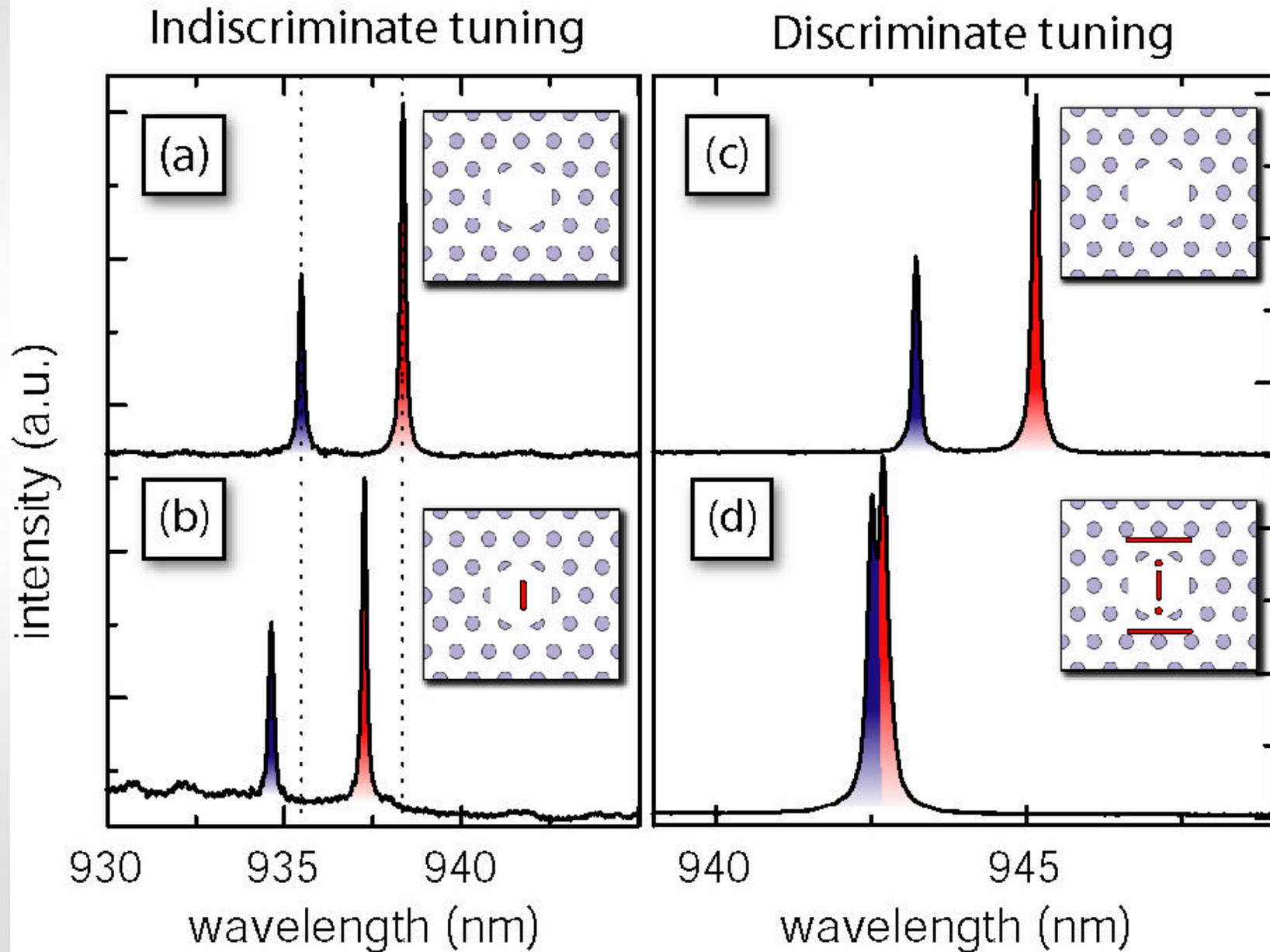
# AFM tuning of PC nanocavities



- Ni/Pt coated tip
- -10 V bias
- 0.1 micron/s scan speed
- oxide is 50 nm X 4 nm



# AFM tuning



# Recent Progress in Strong Coupling

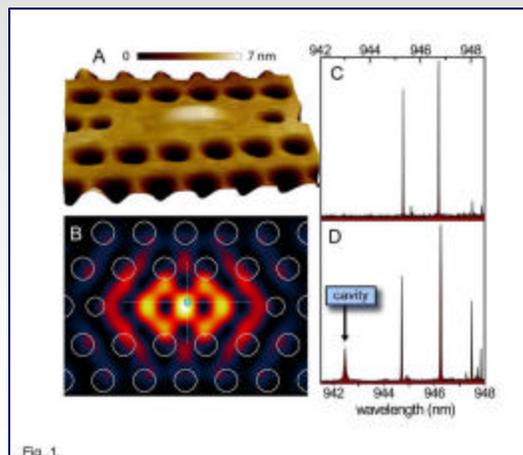
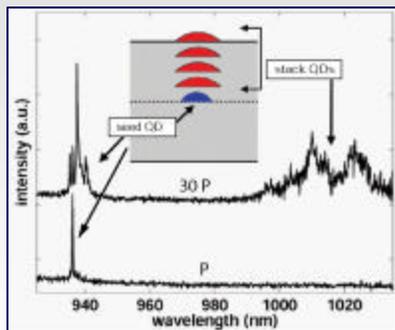


Fig. 1.

## Active-alignment without stacks

- Reduce background emission
- Increase Q of cavity
- Couple to a single QD

## Use of L3 Cavity

Exciton & Mode wavelengths  
as a function of detuning:  
observation of 'anti-crossing'

detuning

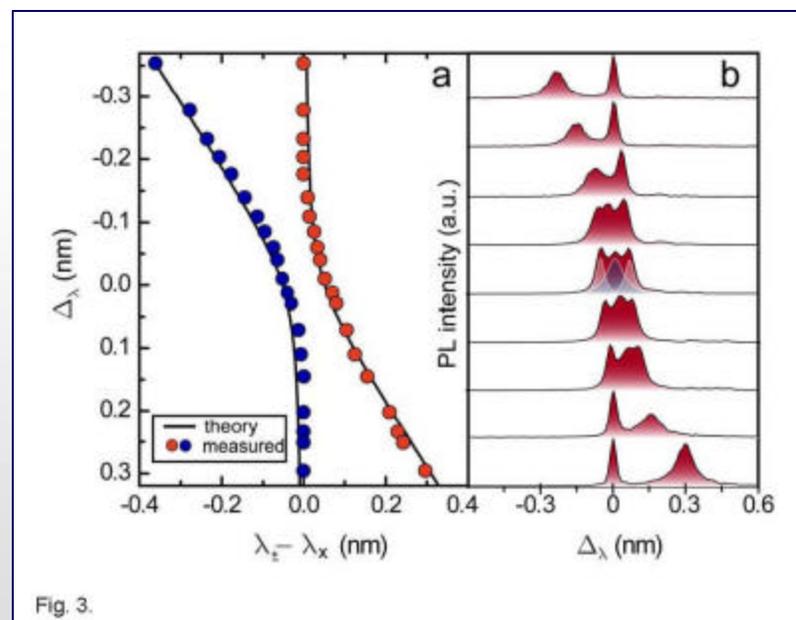
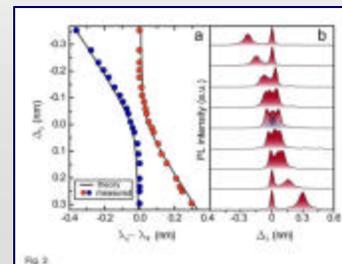
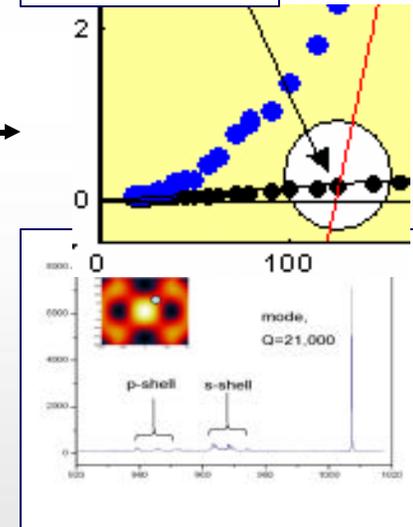
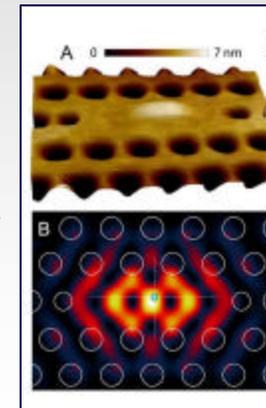


Fig. 3.

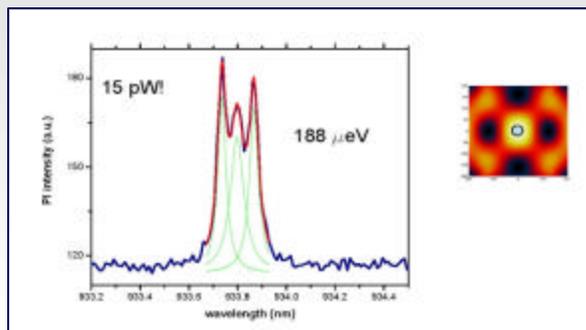
Submitted to *Nature*

# Summary

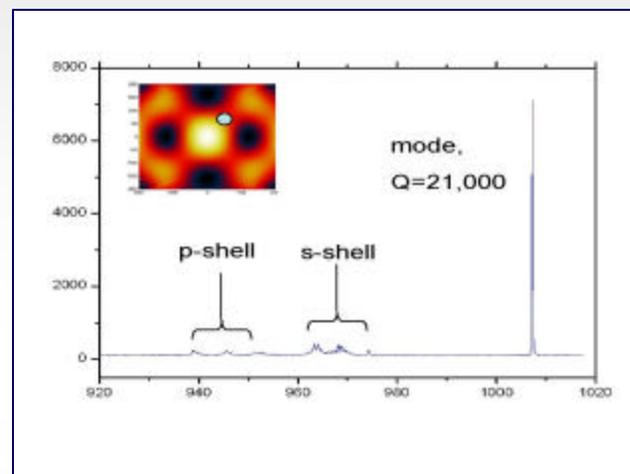
- QD-photonic crystal cavities: powerful tools for Understanding cavity QED in solid state
- Exceptional optical behavior: coupling interactions *without* exact spatial and spectral resonance
- A host of new insights available through single QD interactions with high  $Q$ , small mode volume cavities



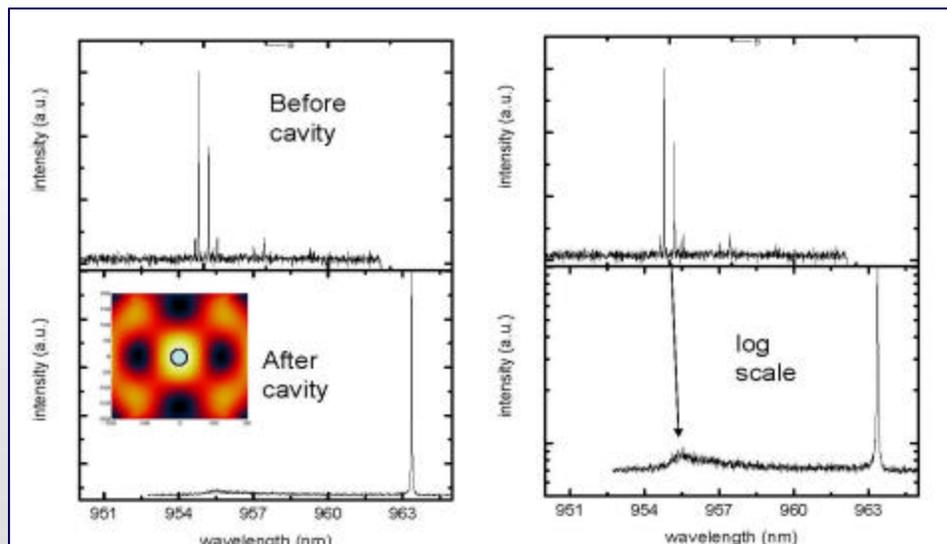
# Questions, questions, questions ...



3-peaks in strongly-coupled spectra  
Exciton-polaritons, cavity



Non-resonant decoration of mode  
(no background coupling)



'cavity draining'?