Frontiers of Nanotechnology:
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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
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.

From Powers of 10

DNA

100 nm

10 nm

1 nm

nano scale

10 nm

DNA

~1-2 nm

Carbon nanotube

5 nm

(P. Alivisatos)

Nanocrystal, aka quantum dot
New Nanoscale Building Blocks with exceptional properties

Carbon Nanotubes as Transistors

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

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

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


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’

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

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


'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]

Promise: manipulating coherent populations of electrons, photons, spin
Control & Coherence: new means of information processing


'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


'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)

<table>
<thead>
<tr>
<th>Photon confinement</th>
<th>Electron confinement</th>
<th>Cavity-QED</th>
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<tbody>
<tr>
<td>High $Q$, small modal volumes</td>
<td>InAs self-assembled quantum dots</td>
<td>- single photon sources - entangled photon pair generation</td>
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'atom-like' spectra

sharp excitonic transitions
Exciton/cavity-mode coupling

- Purcell effect
- single photon sources
- entangled photons
- entangled exciton/photon states
- single photon sources
- quantum gate operations
Semiconductor Quantum Dots

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

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

- 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 (~ few µeV) for single QDs
Discrete excitonic transitions observed

'high optical efficiency emitters, narrow linewidths'

PL at 4K
Photonic crystals selected as optical cavities since they can support modes of ultra-small volume and high ($>1000$) quality factor ($Q$) (gallium arsenide, GaAs)
Tuning the Theoretical $Q$

$V_{\text{eff}} = 0.74 \left(\frac{\lambda}{n}\right)^3$

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

Mode maximum within semiconductor

$V_{\text{eff}} = 0.70 \left(\frac{\lambda}{n}\right)^3$

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

Minimize vertical loss
Fabrication of Photonic Crystal Membranes

1. Electron-beam lithography
2. Dry anisotropic etching
3. HF selective wet etch

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
- cw diode laser (780 nm)
- He-flow cryostat (T = 5K)

- Discrete QD exciton transitions
- High Q cavity transition
- Spatial resonance
- Spectral resonance
Light Amplification from Randomly Positioned QDs

- **Modified L3 cavity**
- **Field stays away from interface**
- **QD density** ~10 µm⁻² from AFM
- **Size and position optimized for high Q and high n_{eff}**
- **Quality factor** Q ~ 18000
- **Mode volume** V ~0.68(λ/n)³
- **Effective index** n_{eff} ~ 2.9
- Strauf et al., Phys.Rev. Lett. 96, 127404/1-4 [2006]
Exceptional lasing performance

Lasing observed with low thresholds in ~ 80% of all samples tested
Low density of QDs as gain medium

QD density
5-50 \(\mu m^{-2}\) 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 $X$s (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 mis-alignment

spectral detuning

Intensity (a.u.)

wavelength (nm)

935 940 945 950 955
Spatial alignment: Active Positioning

Vertically stacked quantum dots grown by Antonio Badolato

- 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

1. map
2. position

Resonance not exactly achieved
Achieving Spatial and Spectral Resonance

spatial mis-alignment

spectral detuning

![Diagram showing spatial mis-alignment and spectral detuning with a graph depicting intensity vs. wavelength in nm. The graph highlights peaks at different wavelengths.]
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

Spectral coupling: digital etching
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

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
Recent Progress in Strong Coupling

- 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’
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’?