Measurement Challenges in Nanomanufacturing

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Nanofabrication Research Group

CNST Center for Nanoscale Science & Technology

New England Nanomanufacturing Summit 2010

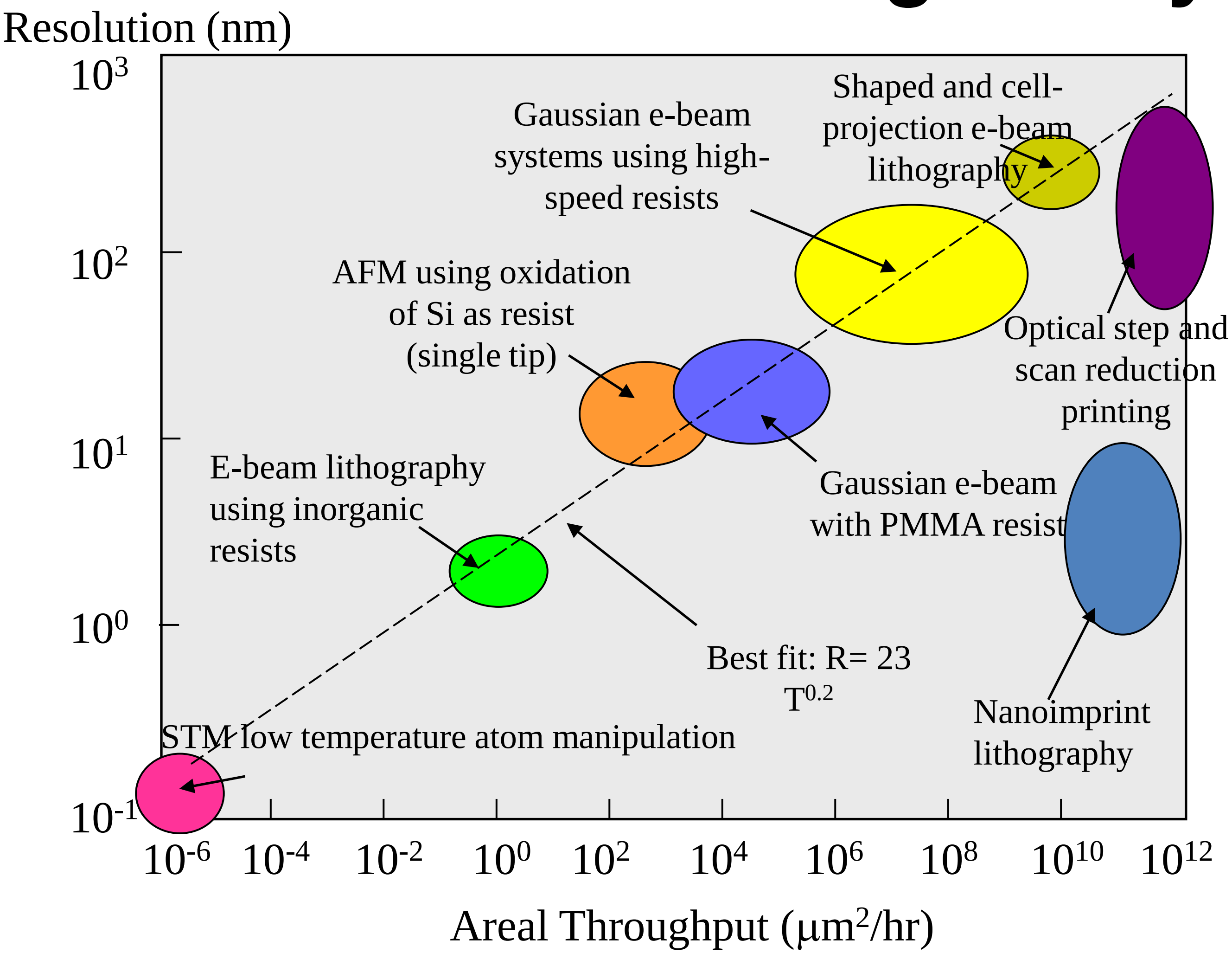
NIST National Institute of Standards and Technology • U.S. Department of Commerce

CNST

- Provides the **measurement and fabrication infrastructure** to support all phases of nanotechnology development from discovery to production.
  - Fee-for-use, state-of-the-commercial-art measurement and fabrication capabilities are provided by developing and maintaining a national shared resource, the **NanoFab.**
  - Beyond state-of-the-commercial-art nanoscale measurement and fabrication solutions are developed and provided using a **multidisciplinary** approach that involves partnering with industry, academia, and government.
- Serves as a hub to **link the external nanotechnology community** to the vast measurement expertise that exists within the NIST Laboratories.
- Helps to **educate** the next generation of nanotechnologist.

www.nist.gov/cnst

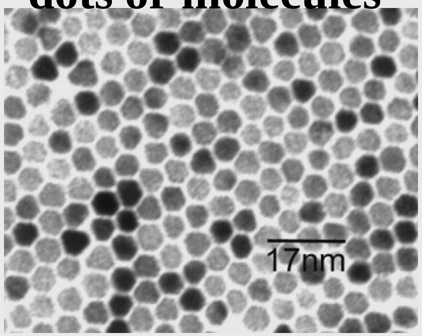
Nanomanufacturing Today



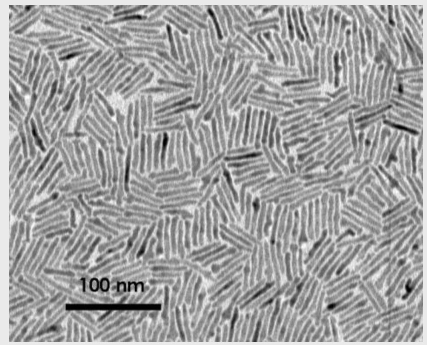
After D.M. Tennant and C.R. Marrian, *J. Vac. Sci. Technol.* (2003)

Nanomanufacturing Tomorrow

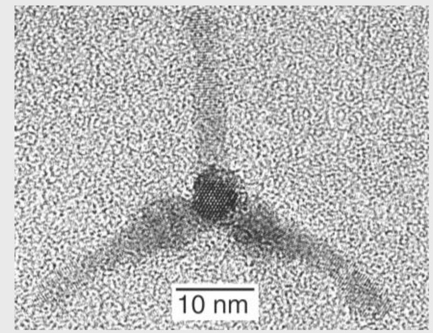
Metal/semiconductor dots or molecules



Rods



Tetrapods



Some assembly required!

- Photovoltaics
- Catalysis
- Water Purification & Photolysis
- Multifunctional Coatings
- Sensors
- Electronics

Where do we need to go?

- 193 nm immersion lithography
  - 40 nm pixels, 3×10^{-3} m^2/s
    - 6.25×10^{14} pixels/m^2, 2×10^{10} pixels/s
- Letterpress
  - 40 μm pixels, 30 m^2/s
    - 5×10^{8} pixels/m^2 , 1.5×10^{10} pixels/s
- 10^4 x areal throughput, 10^6 x feature density

➢ 2×10^{16} 40 nm pixels/s or better

How can measurement help?

- Measurements for fundamental understanding
- Measurements for process/quality control

Metrology Requirements

Table MET2a Metrology Technology Requirements—Near-term Years

Year of Production	*2007*	*2008*	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*	*Driver*
DRAM ½ Pitch (nm) (contacted)	*65*	*57*	*50*	*45*	*40*	*36*	*32*	*28*	*25*	
MPU/ASIC Metal 1 (M1) ½ Pitch (nm)(contacted)	*68*	*59*	*52*	*45*	*40*	*36*	*32*	*28*	*25*	
MPU Physical Gate Length (nm)	*25*	*22*	*20*	*18*	*16*	*14*	*13*	*11*	*10*	
Microscopy										
Inline, nondestructive microscopy process resolution (nm) for P/T=0.1	0.22	0.2	0.18	0.16	0.14	0.13	0.12	0.1	0.09	*MPU Gate*
Microscopy capable of measurement of patterned wafers having maximum aspect ratio/diameter (nm) (DRAM contacts) [A]	16	17	17	>20	>20	>20	>20	>20	>20	*D1/2*
	76	67	60	50	40	35	30	28	25	
Materials and Contamination Characterization										
Real particle detection limit (nm) [B]	25	22	20	18	16	14	13	11	10	*MPU*
Minimum particle size for compositional analysis (dense lines on patterned wafers) (nm)	22	19	17	15	13	12	11	9	8	*D1/2*
Specification limit of total surface contamination for critical GOI surface materials (atoms/cm^2) [C]	5.00E+09	5.00E+09	5.00E+09	5.00E+09	5.00E+09	5.00E+09	5.00E+09	5.00E+09	5.00E+09	*MPU Gate*
Surface detection limits for individual elements for critical GOI elements (atoms/cm^2) with signal-to-noise ratio of 3:1 for each element	5.00E+08	5.00E+08	5.00E+08	5.00E+08	5.00E+08	5.00E+08	5.00E+08	5.00E+08	5.00E+08	*MPU Gate*

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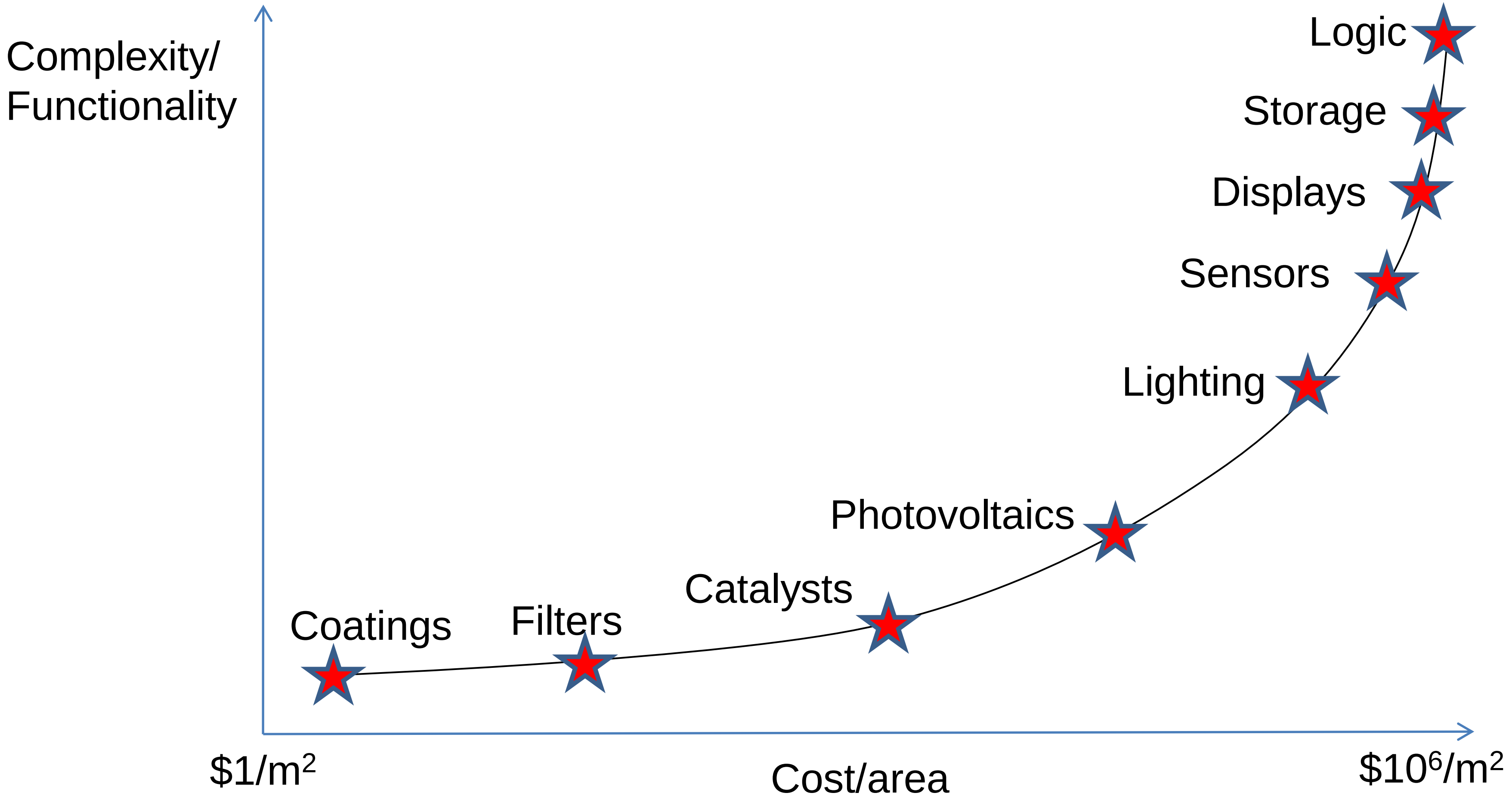
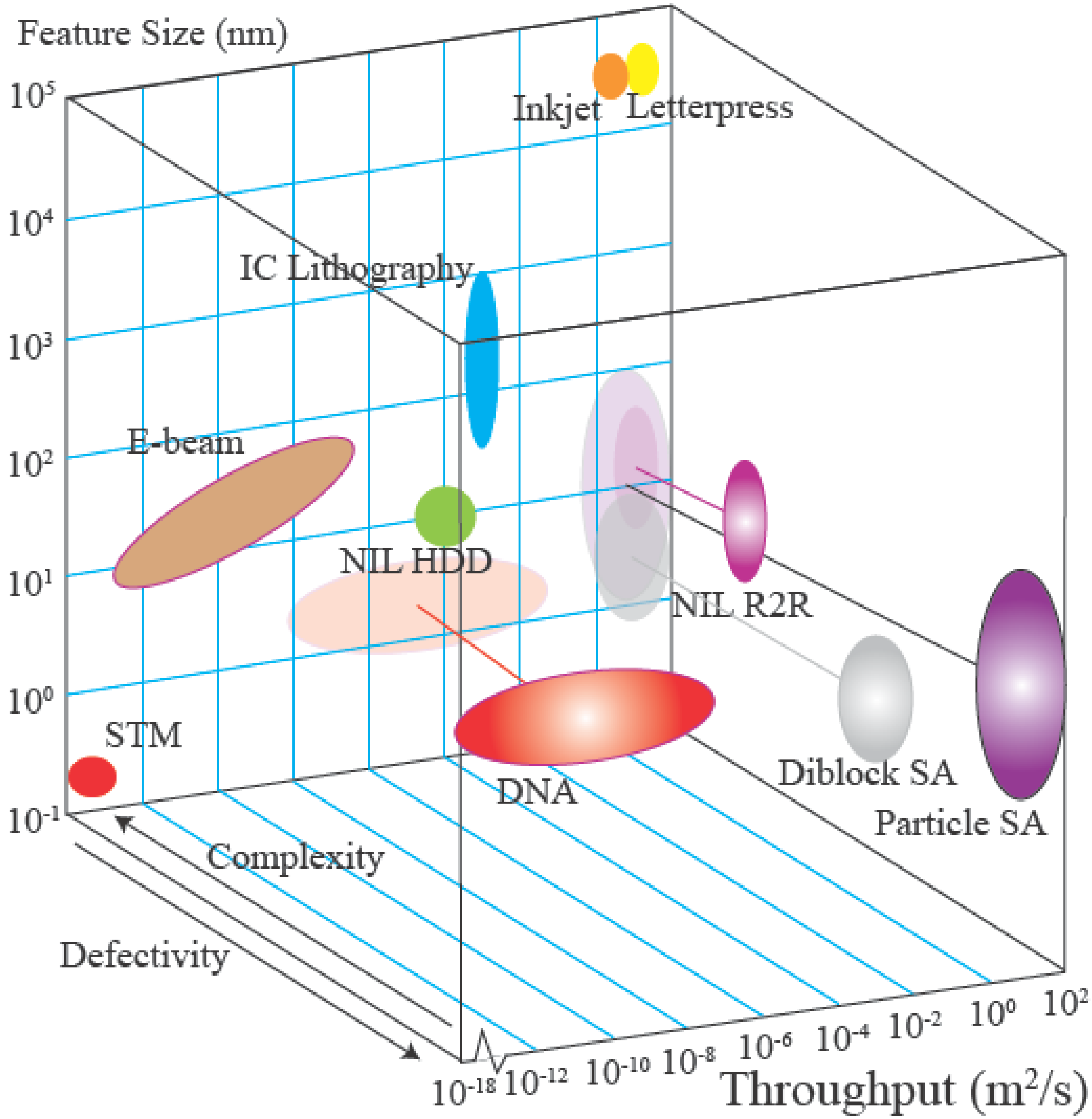
The Cost of Complexity

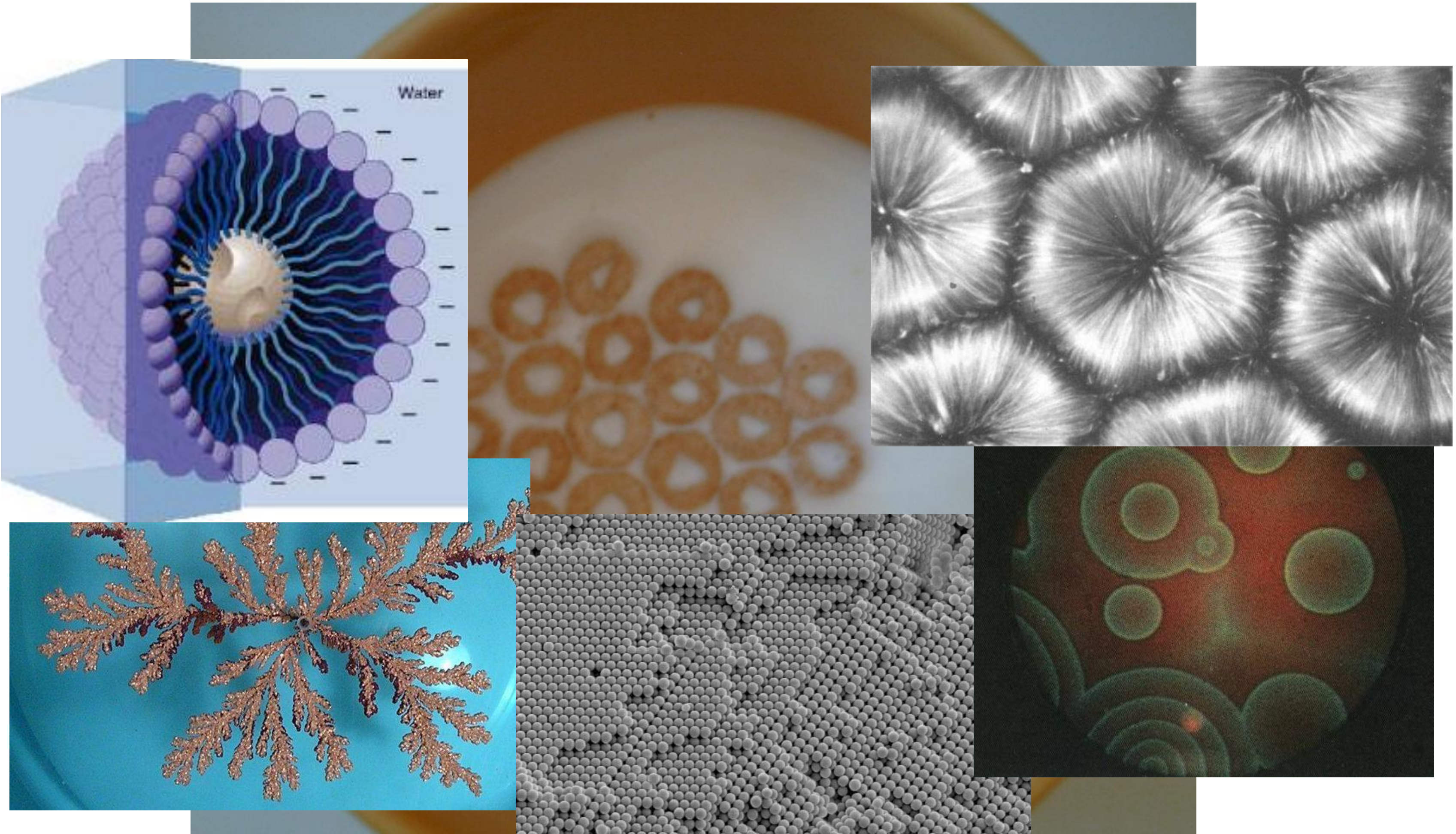



Feature Size (nm)
10^5
10^4
10^3
10^2
10^1
10^0
10^-1
Inkjet
Letterpress
IC Lithography
E-beam
NIL HDD
NIL R2R
STM
DNA
Diblock SA
Particle SA
Complexity
Defectivity
10^-18 10^-12 10^-10 10^-8 10^-6 10^-4 10^-2 10^0 10^2
Throughput (m²/s)

What measurements are needed?

- Measurements for fundamental understanding
  - Slow, expensive, infrequent
    - New measurements needed for novel materials/devices fabrication processes
- Measurements for process/quality control
  - Fast, cheap, periodic or continuous
    - Off-line
    - Real-time

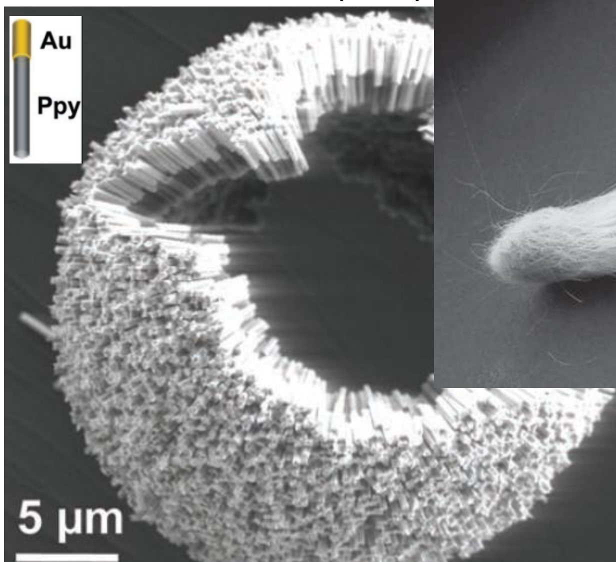
Self Assembly Everywhere

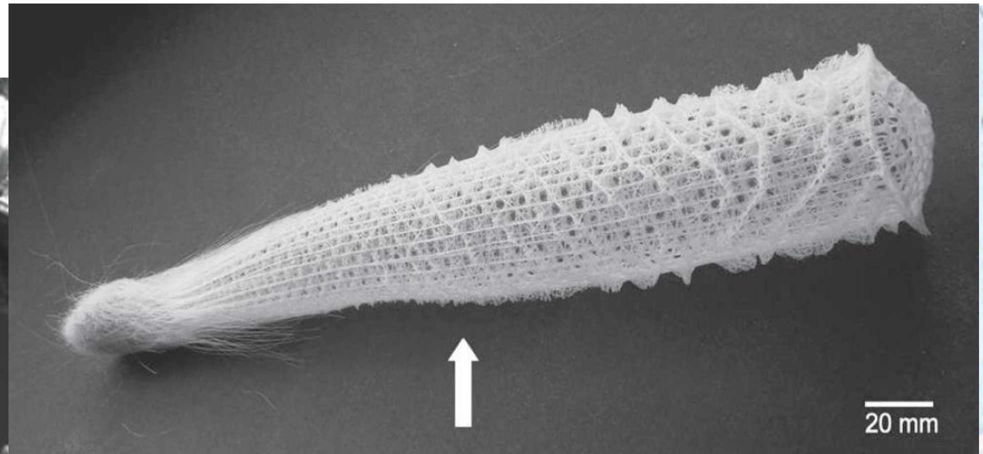


Self-Assembly at All Scales, G.M. Whitesides and B. Grzybowski, *Science* (2002)

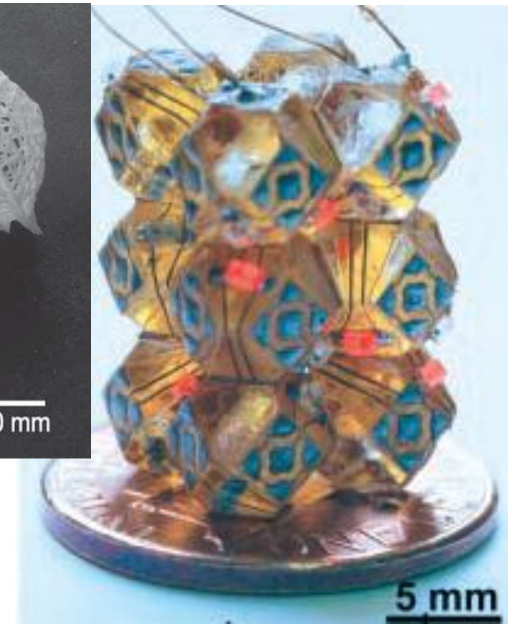
Directed Self-Assembly

Park et al., Science (2004)

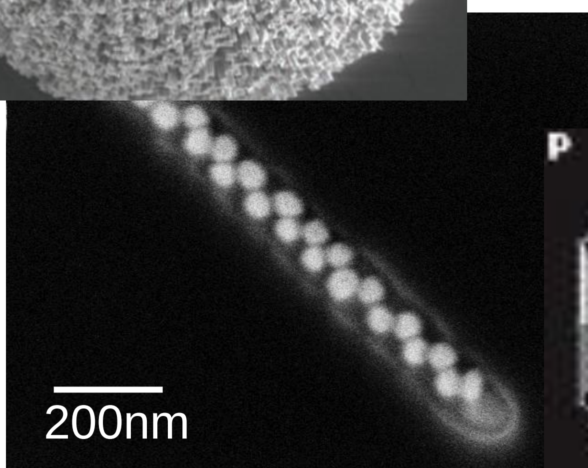




Woesz, J. Mat. Res. (2006)

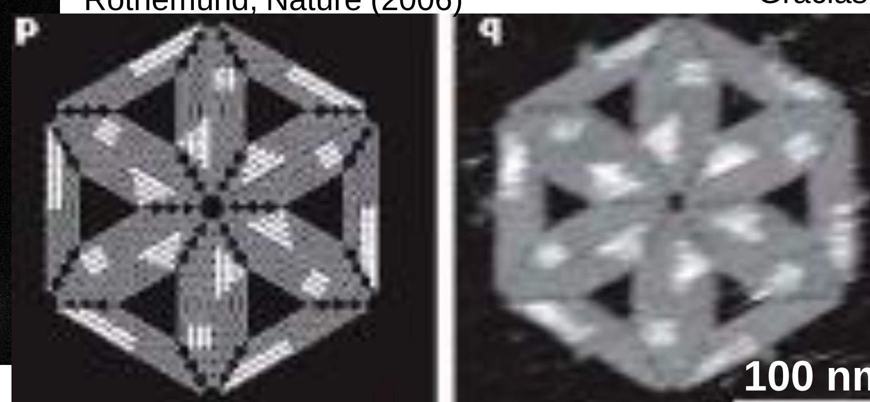


Gracias et al. Science (2000)

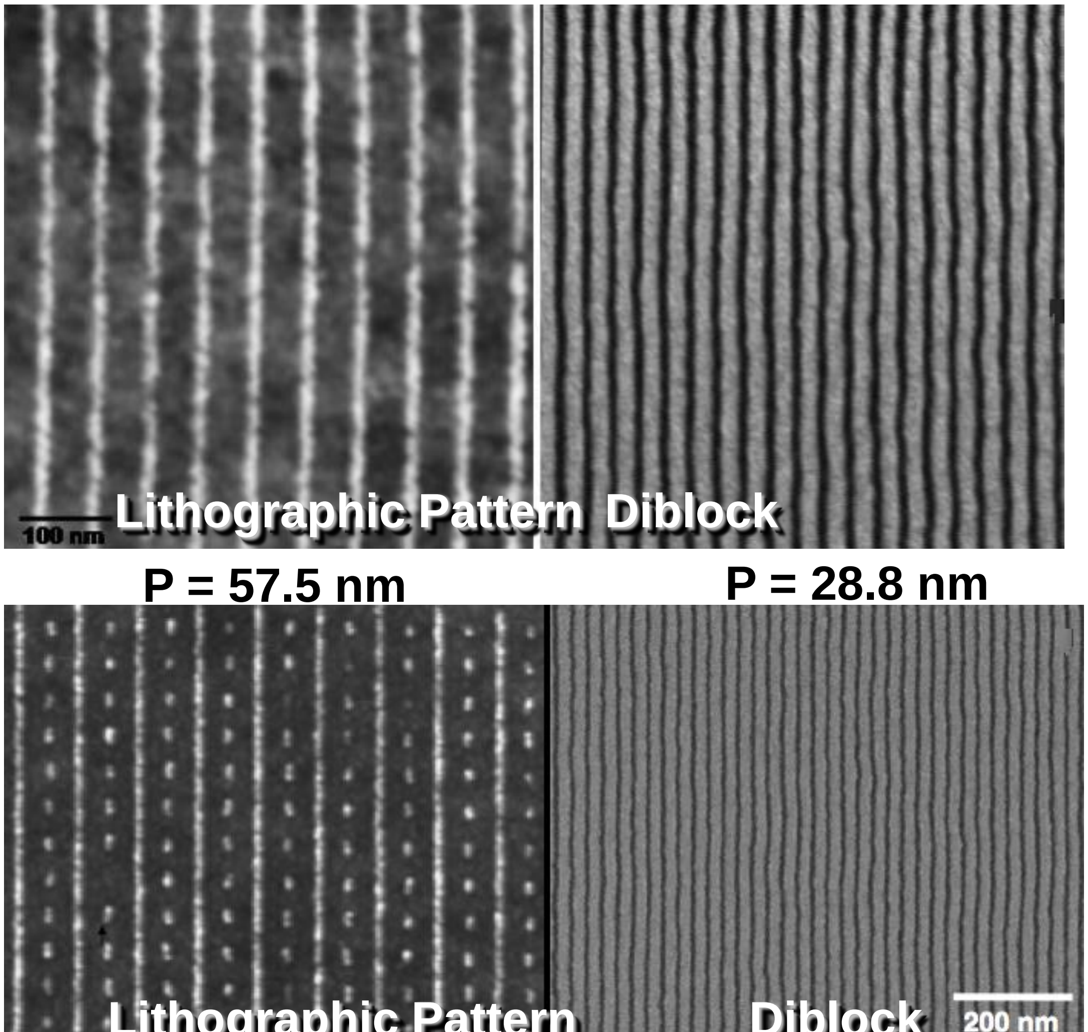


Cui et al. Nanoletters (2004)

Rothemund, Nature (2006)

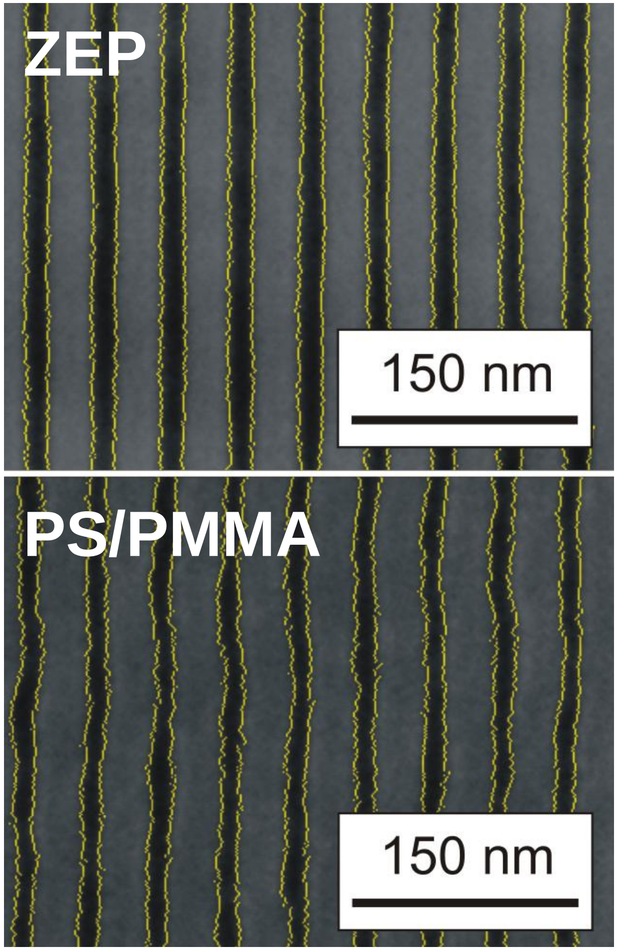


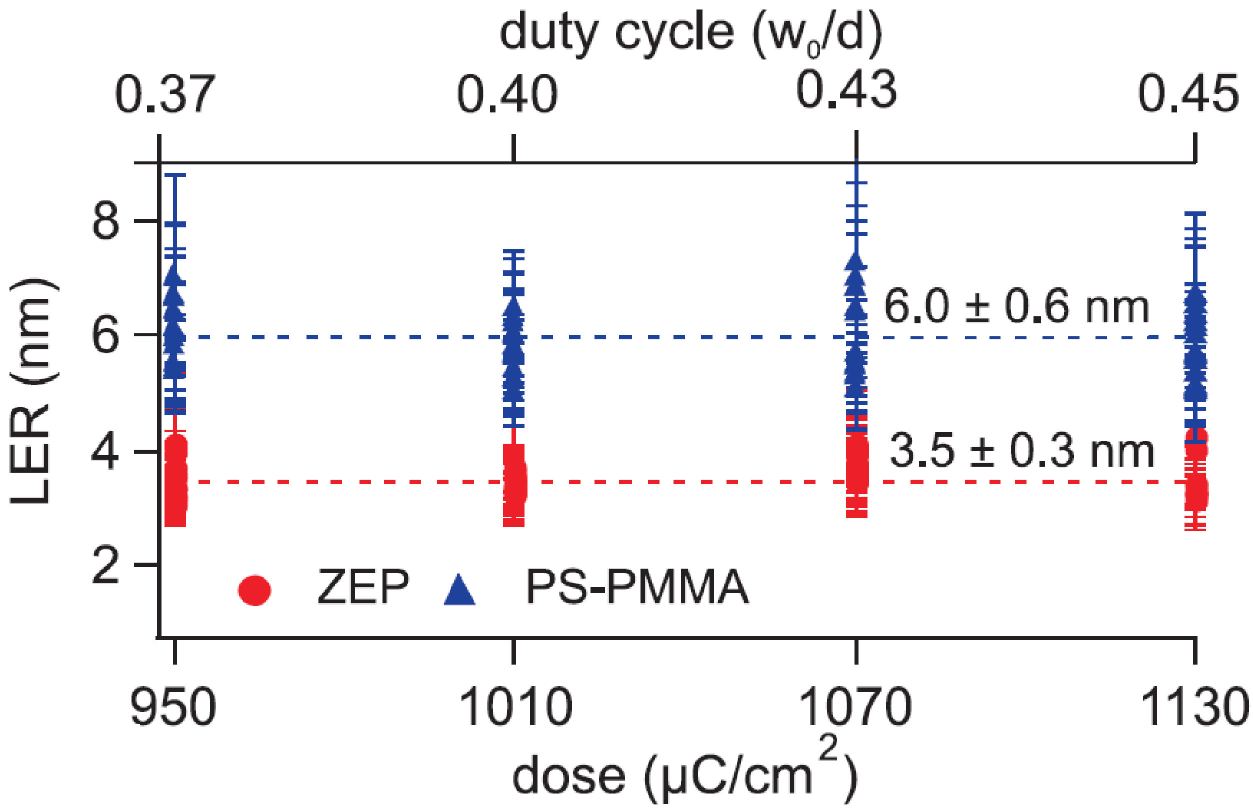
Sub-Lithographic Patterns



Dense Self-Assembly on Sparse Chemical Patterns: Rectifying and Multiplying Lithographic Patterns Using Block Copolymers, Joy Y. Cheng, Charles T. Rettner, Daniel P. Sanders, Ho-Cheol Kim, and William D. Hinsberg, Advanced Materials, (2008) - IBM

LER from SEM

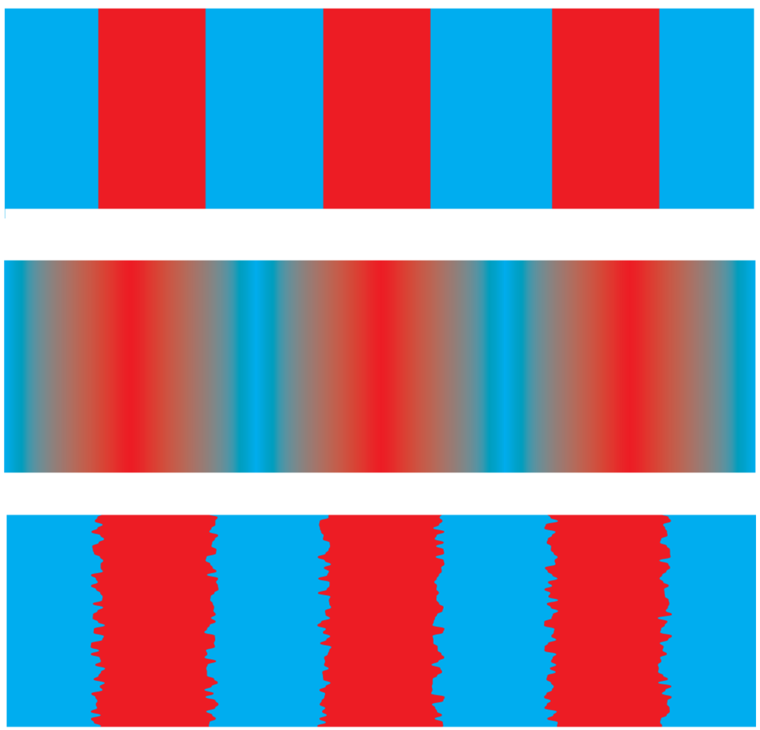




J.A. Liddle, Gila Stein, CNST

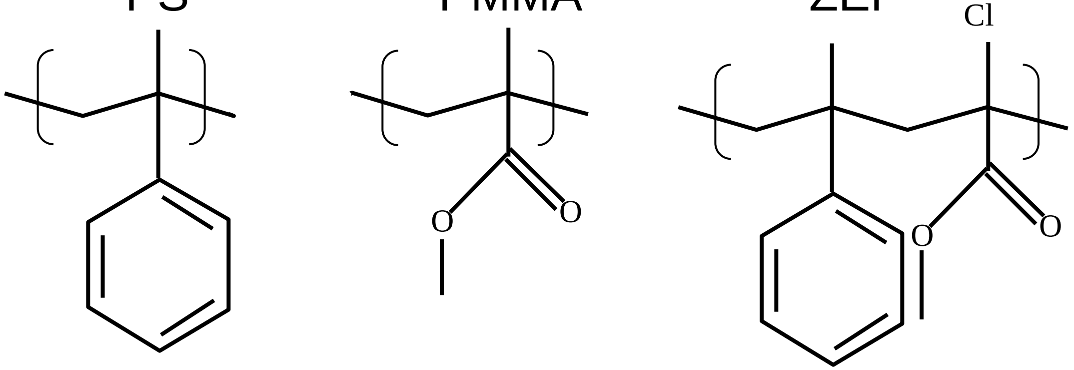
Resonant X-ray Scattering

Are interfaces sharp, chemically diffuse or rough?

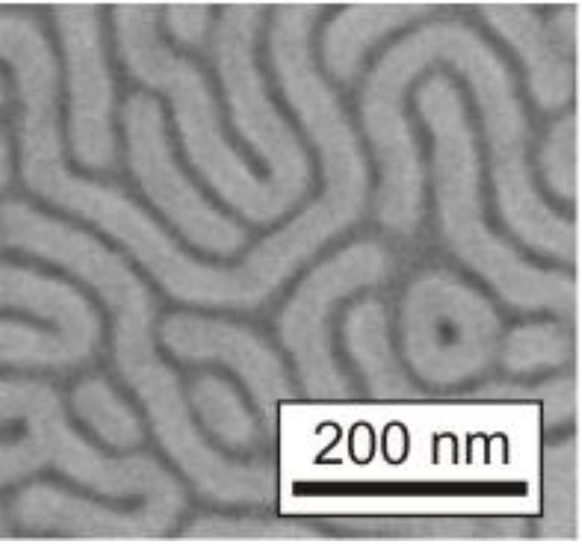


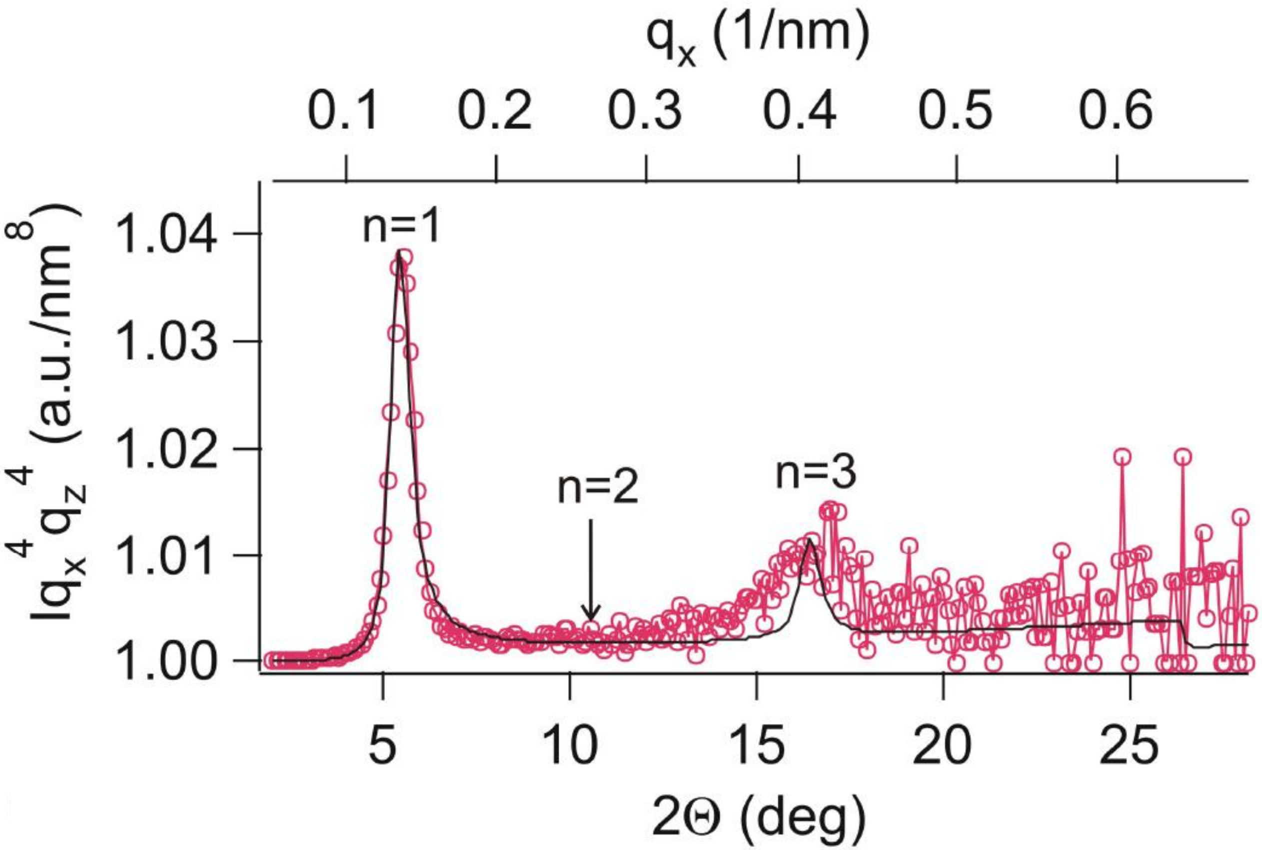
Virgili et al. Macromolecules (2007)

- X-ray scattering can measure interfacial width or roughness to sub-0.5 nm accuracy.
- Different chemistries have distinct resonances
- Resonant scattering enhances contrast from different chemical domains
- C=C π^* 285 eV, C=O π^* 288 eV, C-O σ^* 293 eV

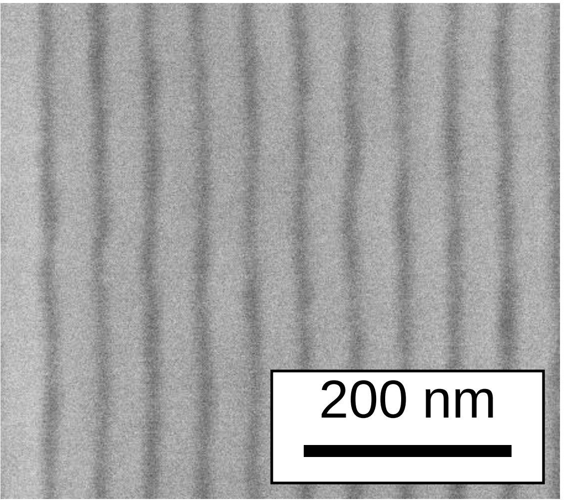


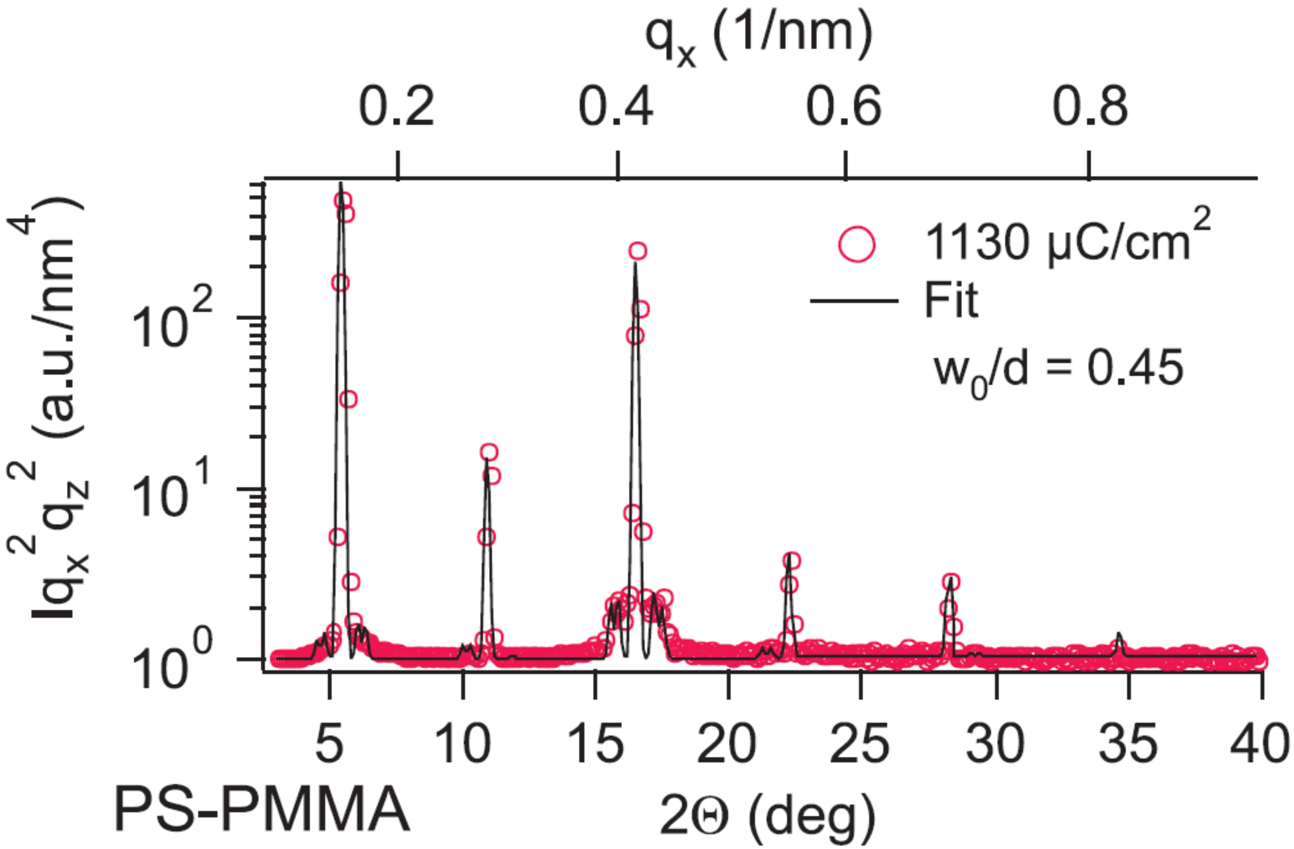
Random Diblock Diffraction





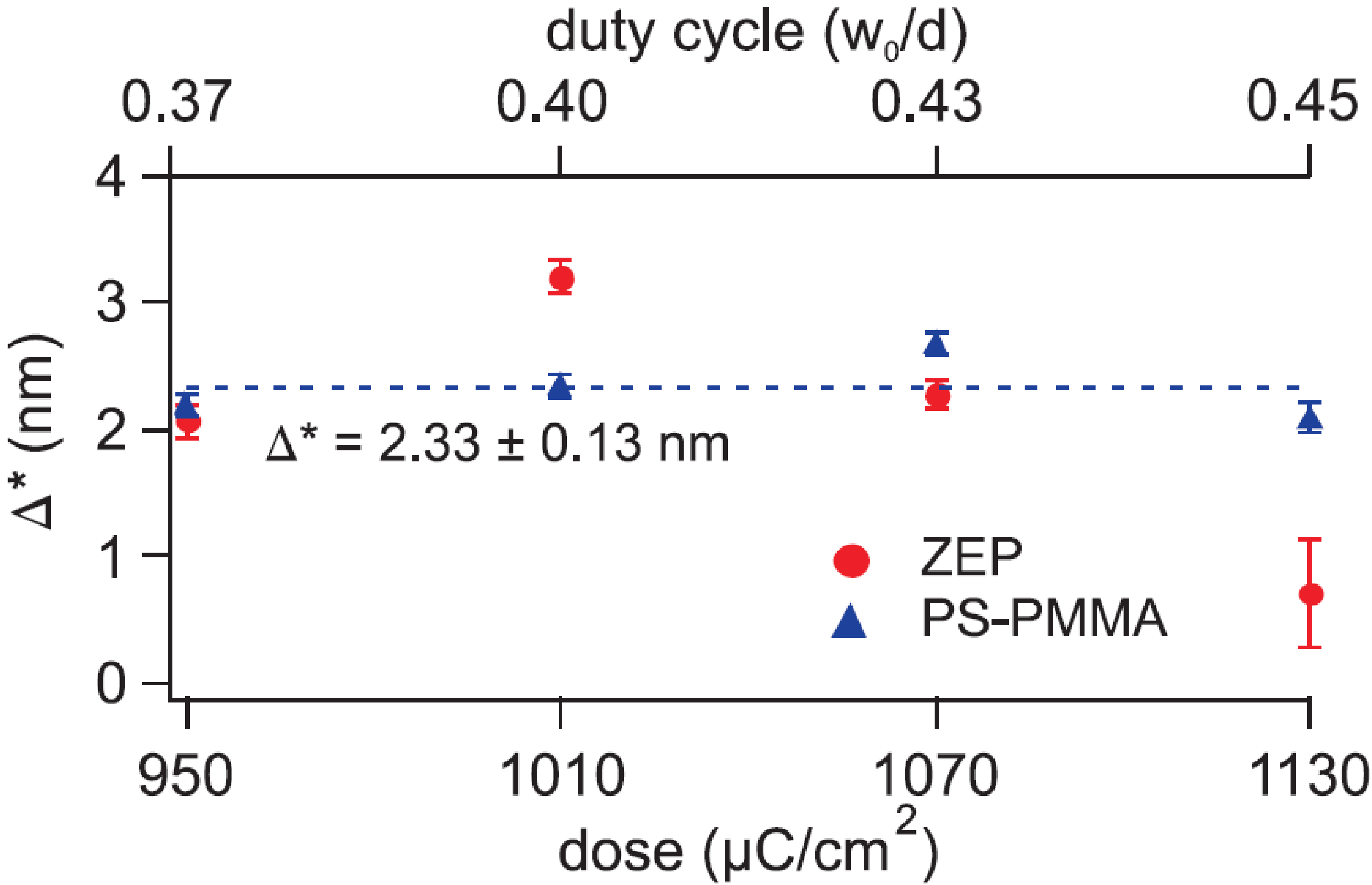
Epitaxial Diblock Diffraction



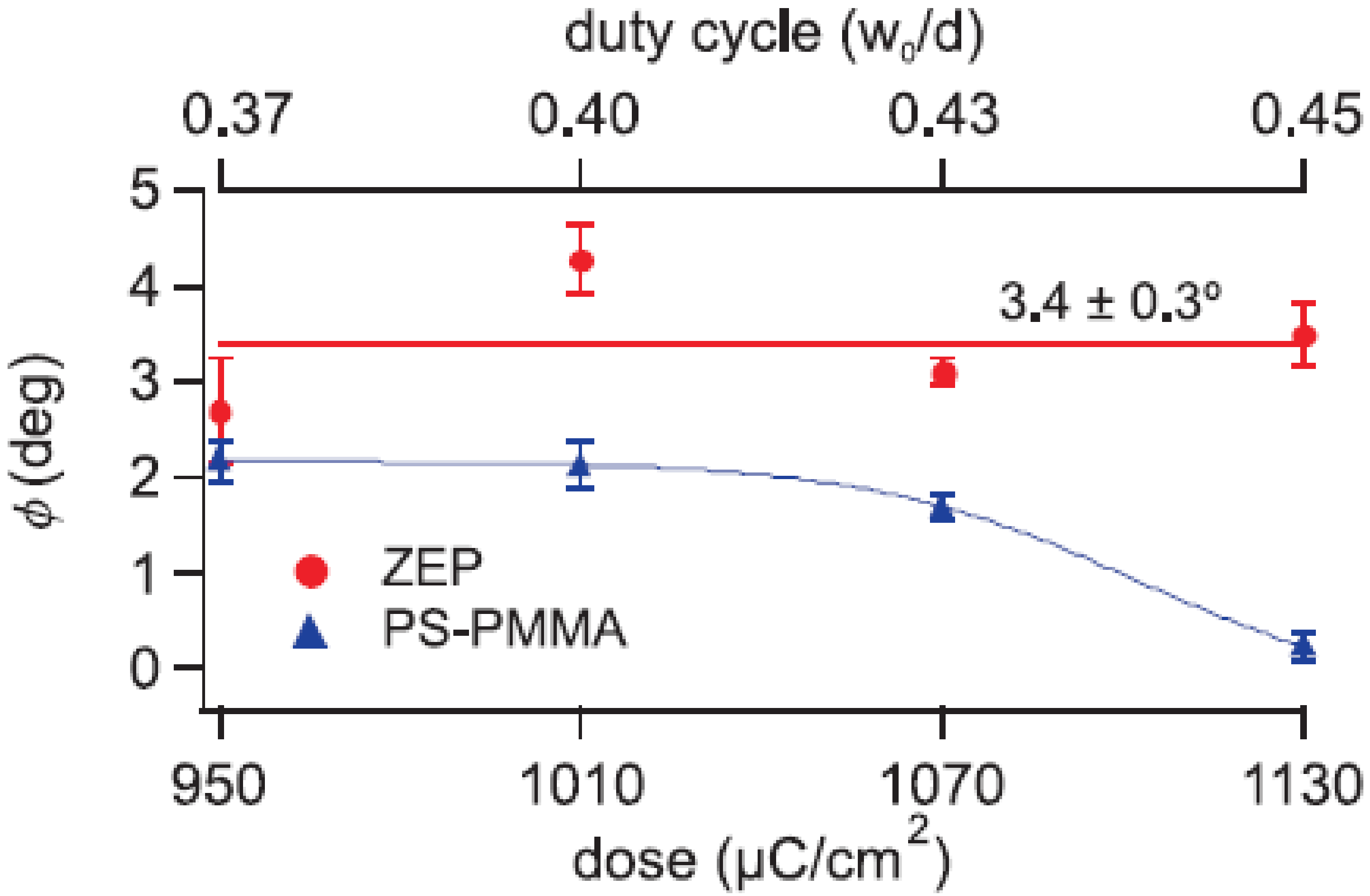


PS-PMMA

Interface Width from XRD

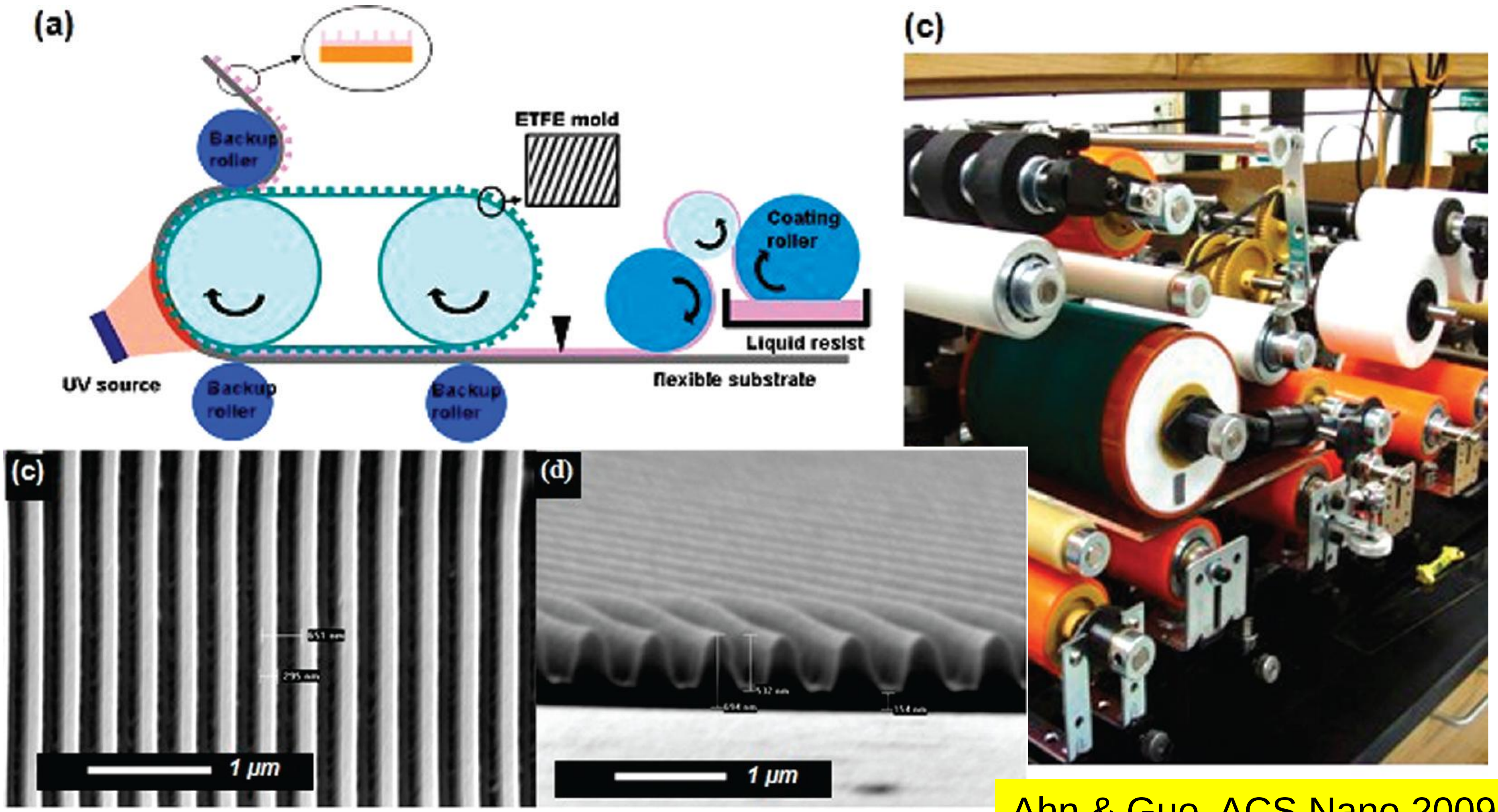


Sidewall Angle



G.E. Stein et al. *Macromolecules*, **43** 433 (2010)

Roll-to-Roll Imprint



Ahn & Guo, ACS Nano 2009

Metrology Requirements for R2R Diblocks

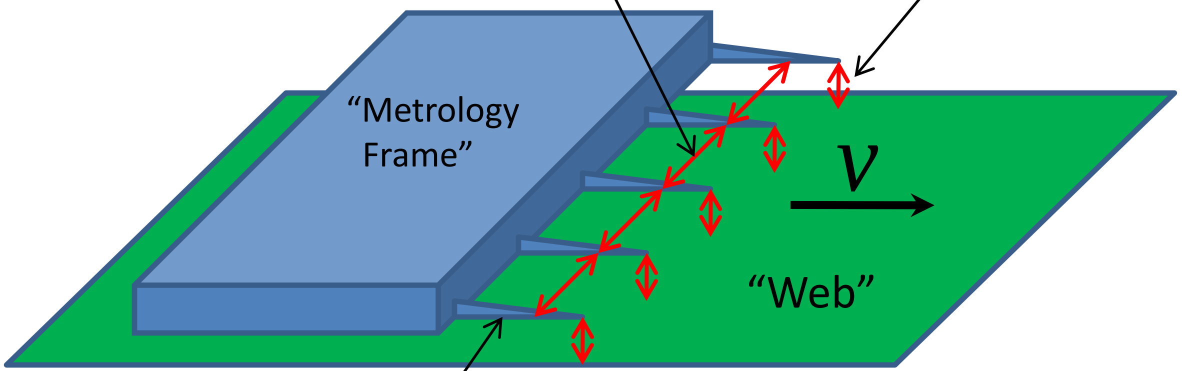
- Determine short range and long range orientation, order, defectivity, thickness, …
- Challenges:
  - Feature sizes down to a few nm
  - Substrate (“web”) speeds up to meters/second
  - Cost
- Techniques:
  - In-plane polarization analysis
  - Scattered light surface roughness measurement
  - Nano-plasmonic near-field sampling
  - Normal incidence interferometry
- All techniques will require a high level of model development to enable data extraction
- Low-cost/High-speed requirement → Measurement technique must be specific to the type of pattern being measured

High-Speed Near-field Measurement

- Metrology frame contains “laser gauges”
    - Know spacing between read heads to ~nm
- Read heads operate as in disk drive
    - “fly” above web surface: Height ~ several nm
    - Move up and down: Track surface undulations
- Read heads are “functionalized” with a near field imaging system specific to the pattern being measured
    - …NSOM, guided modes, plasmonic, interferometric, polarization …
- Near field sensors give local nm scale resolution
    - Sense Local Order
- Laser gauges allow for correlation of signals from separate sensors
    - Compute Long Range Order

"Laser Gauges" track the relative position of each sensor arm to nm precision
→ Determine long range order.

Each sensor head is functionalized to measure precisely the type of pattern(s) being generated on the "web"
→ Determine short range order

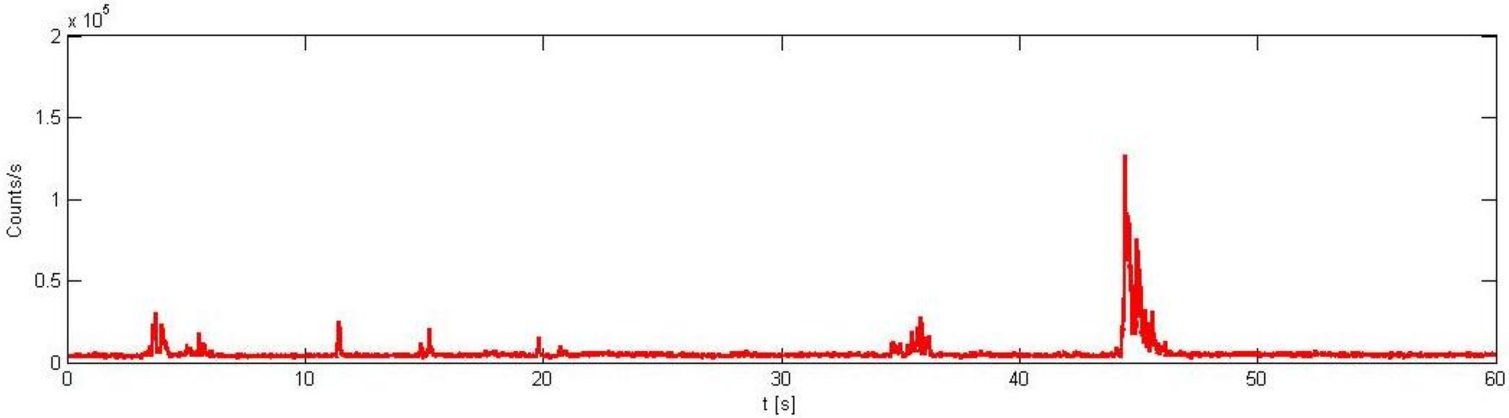


"Flying Height Sensor" arms from hard disk read heads.

- "Float" a few nm above the "web"
- Automatically (aerodynamically) move up and down to track vertical deviations in the "web" top surface position

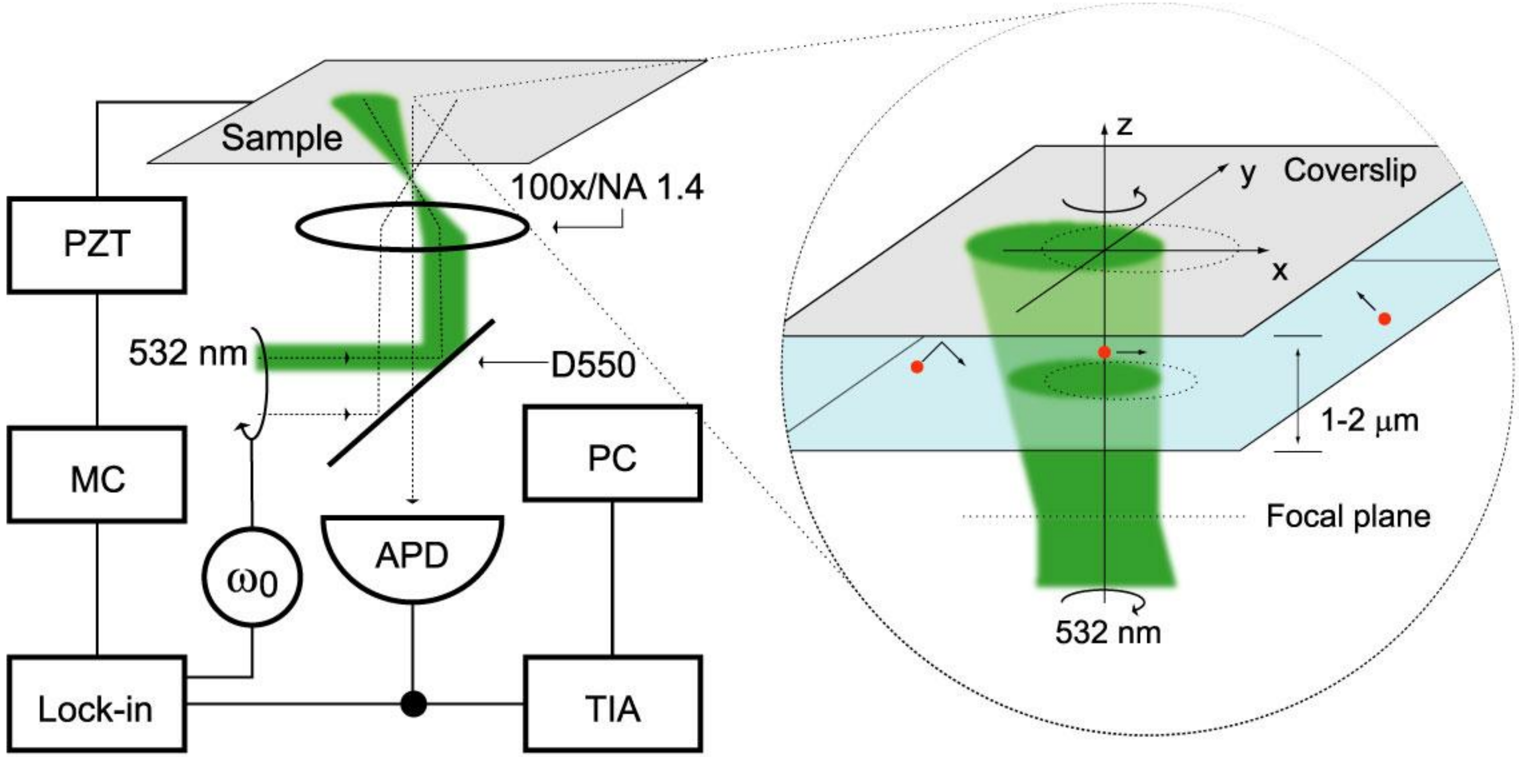
Single-Molecule/Nanoparticle Behavior

- Brownian motion limits the dwell time of single molecules in a diffraction-limited microscope observation volume
- Tracking-FCS uses feedback control to combine the spatial resolution of single-particle tracking with the temporal resolution of fluorescence correlation spectroscopy, all with a single molecule or nanoparticle
- The method is sensitive to rotational motion, conformational changes, binding/unbinding – anything that affects fluorescence intensity



- In open-loop configuration, 60-nm diameter particles diffuse across the beam in 100 ms – 300 ms

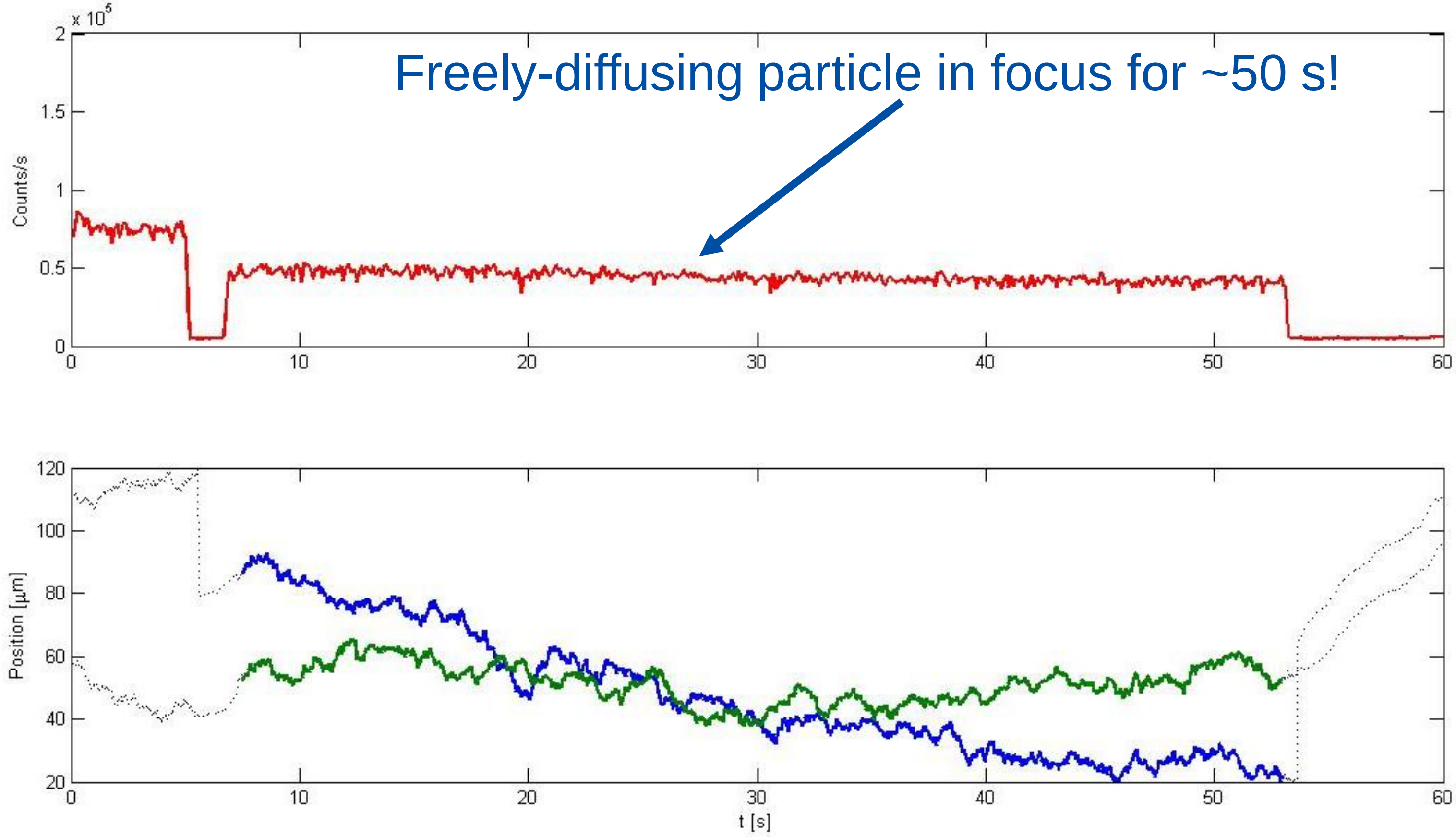
Controlling Brownian Motion



A. J. Berglund and H. Mabuchi, "Tracking-FCS: Fluorescence correlation spectroscopy of individual particle," Optics Express **13**, 8069-8082 (2005)
A. J. Berglund, K. McHale and H. Mabuchi, "Fluctuations in closed-loop fluorescent particle tracking," Optics Express **15**, 7752-7773 (2007)
K. McHale, A. J. Berglund, and H. Mabuchi, "Quantum dot photon statistics measured by three-dimensional particle tracking," Nano Letters **7**, 3535-3539 (2007)

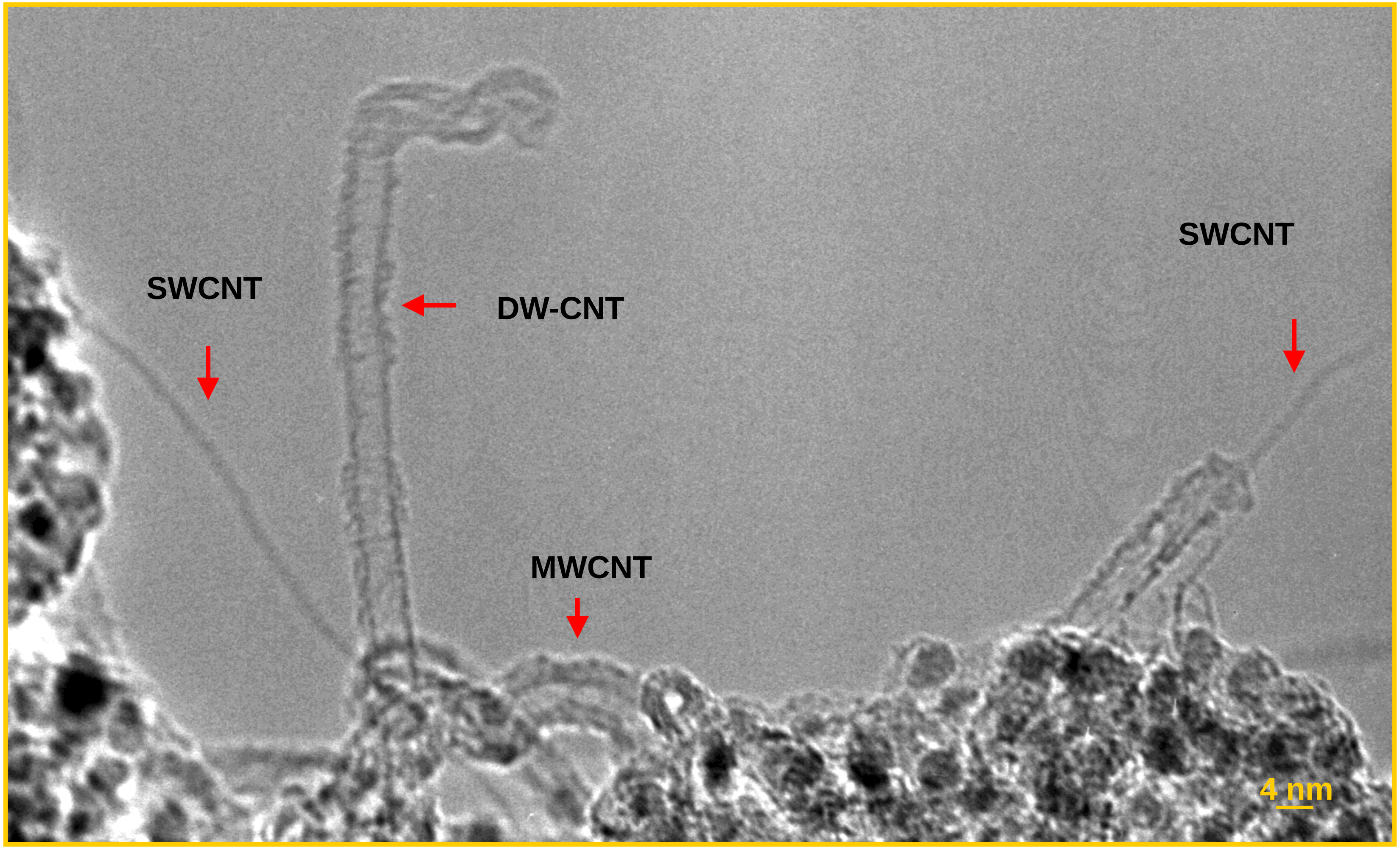
- Rotating the laser focus encodes a single particle's position
- Translation of the sample locks a particle to the observation volume

Controlling Brownian Motion



- In closed-loop mode, single-photon fluorescence signal (top) and particle position (bottom) are collected simultaneously for a single particle

Morphological Diversity in CNTs



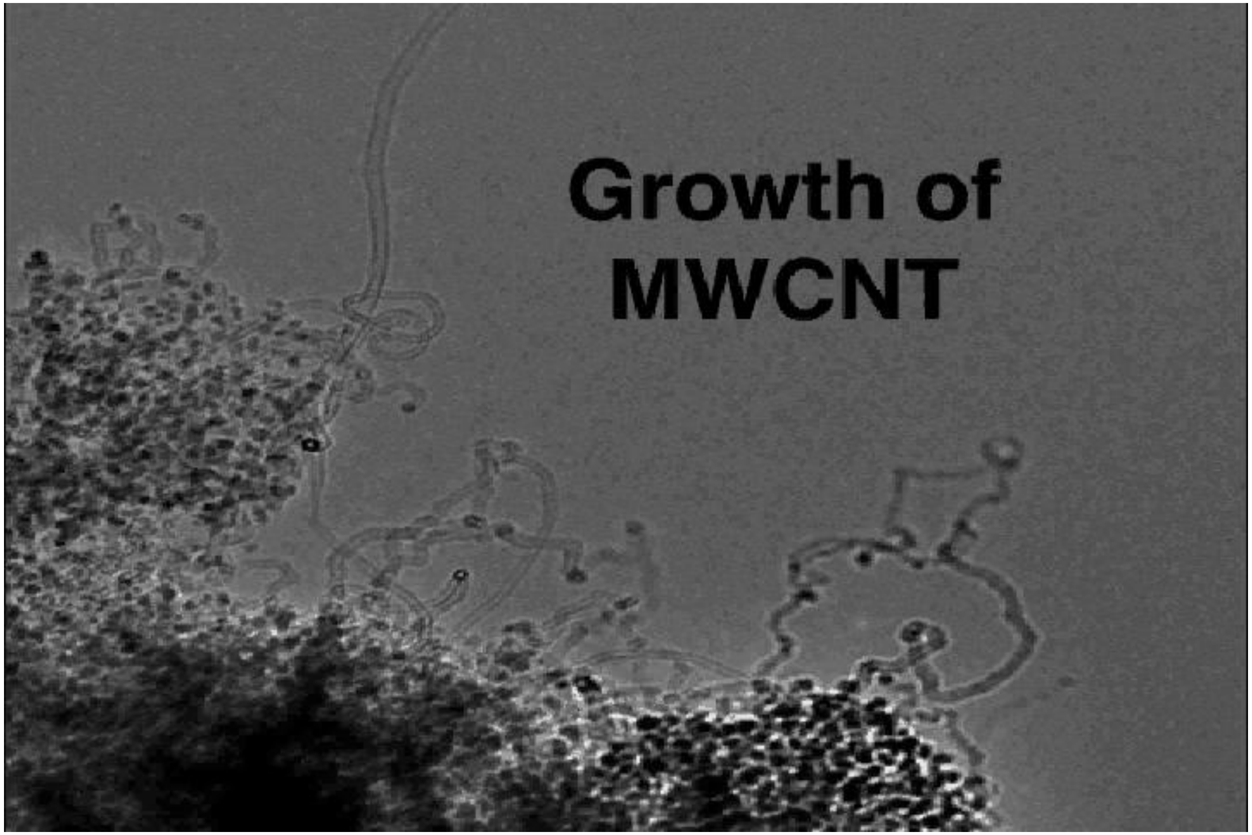
Growth at 500^{o}C in 300 mTorr of C_2H_2

Sharma and Iqbal, Appl. Phys. Lett. **84** 990 (2004)

Factors Controlling the Catalytic CVD Synthesis of CNTs

- Catalyst: Ni, Cu, Co, Fe, Mo and bimetallic catalysts
- Support: SiO_2, MgO, TiO_2
- Temperature: 500°C – 1000°C (400 °C -700 °C)
- Precursor: Hydrocarbons (CO, CH_4, C_2H_4, C_2H_2 etc.)
- Pressure: 760 Torr (1 - 300 mTorr)

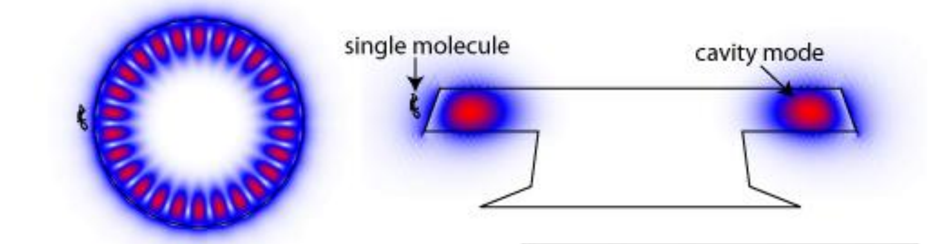
Environmental TEM

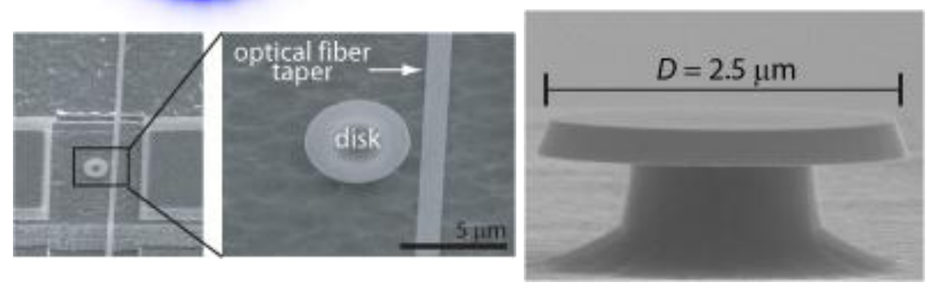


THANK YOU!

Nanophotonic cavities for single molecule detection

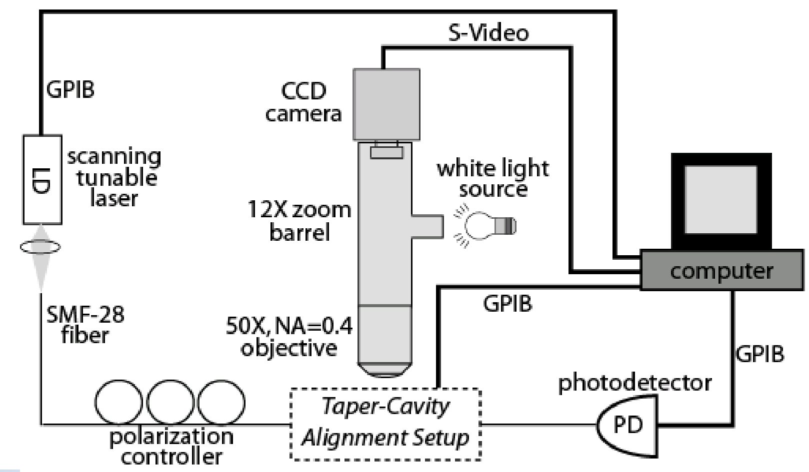
- **Label-free, single molecule sensitivity due to:**
  - High quality factors (long photon interaction time)
  - Wavelength-scale light confinement (strong light-matter interaction)





(K. Srinivasan and O. Painter, *Nature*, 2007)

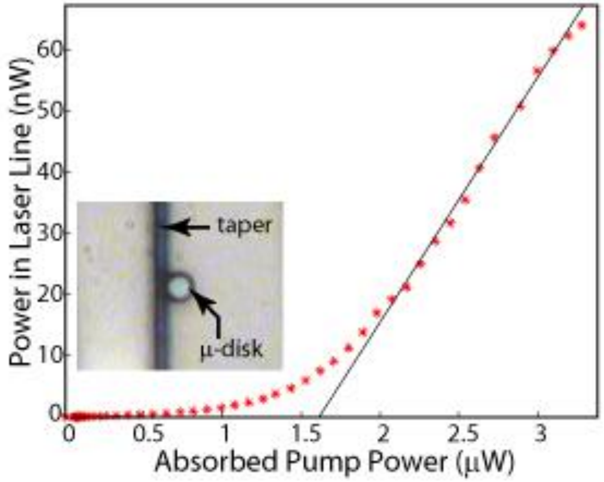
- First demonstration: Armani et al, *Science*, 2006 – Single molecule detection of interleukin-2 in a 80 mm diameter, toroidal glass microcavity

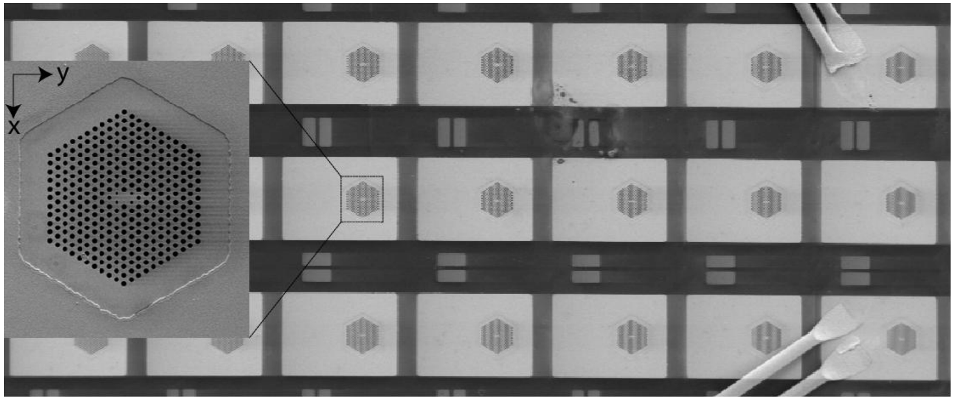


Nanophotonic light sources for chip-level spectroscopy

- **Nanofabricate optical resonators in light-emitting media to create on-chip lasers and LEDs for spectroscopy applications**
  - 2D arrays of devices on a chip
  - Tune resonator geometry across array for multi-wavelength device
  - Optimized device geometries for in-plane or vertical emission, depending on application
  - Can be integrated with microfluidics for sample delivery to sensing region

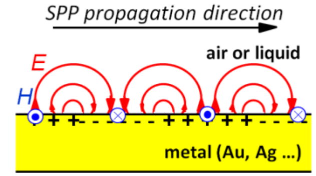
Fiber-coupled microdisk lasers (K. Srinivasan et al, *Opt. Express*, 2006)



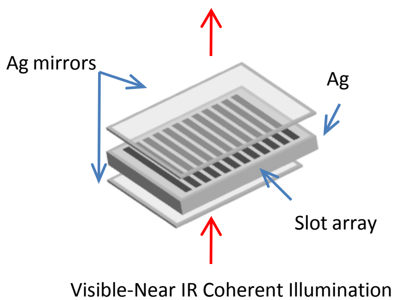


Nanoplasmonic Optical Resonators For Biosensing

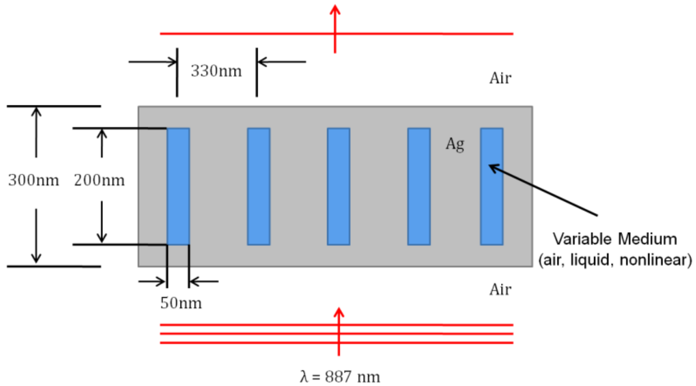
- Plasmons confine light to nanoscale dimensions
- Array of slots gives high-Q resonator
- Transmission very sensitive to index in slots



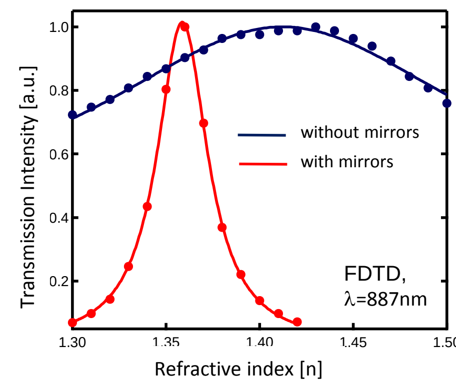
SPP at metal-dielectric interface



a) Device Perspective

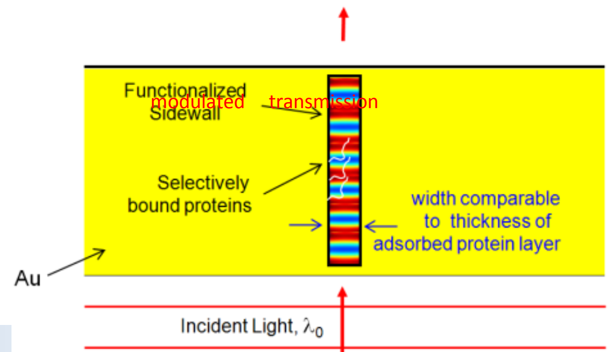


b) Device Cross Section



c) Simulated transmission v.s. index of cavity medium

- Nanoscale volume and sensitivity can yield label-free sensing of molecules selectively bound to cavity walls

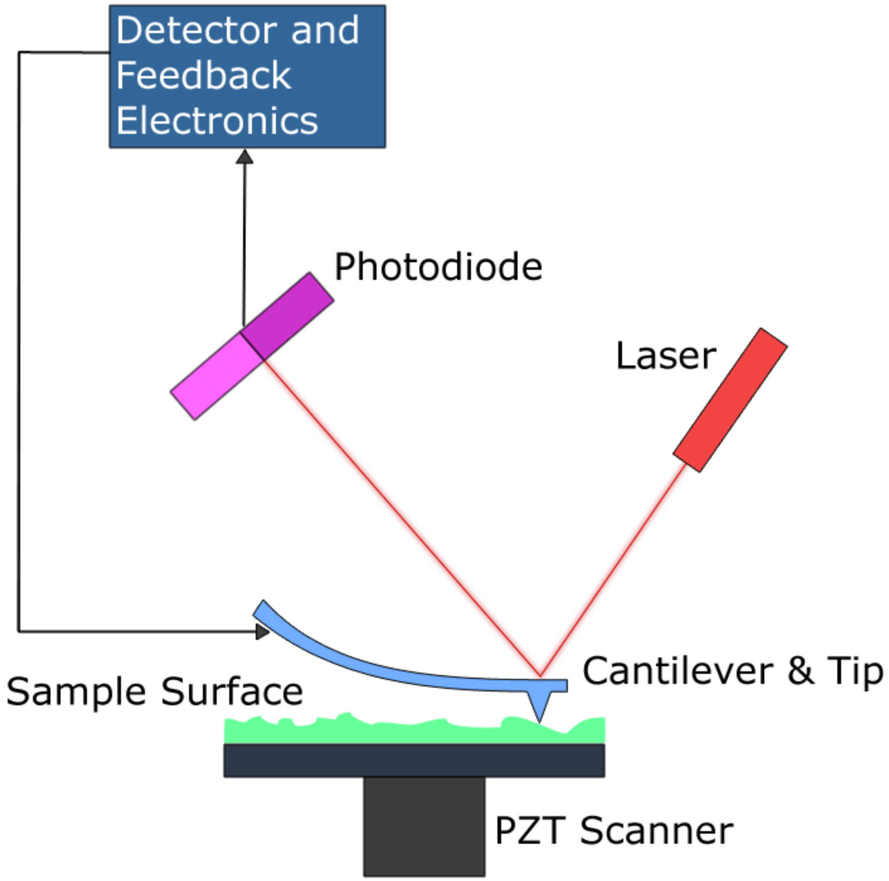


H. Lezec, A. Agrawal, J. Weiner, M. Abashin, CNST

Pacifici et al., Nature Photonics (2007)

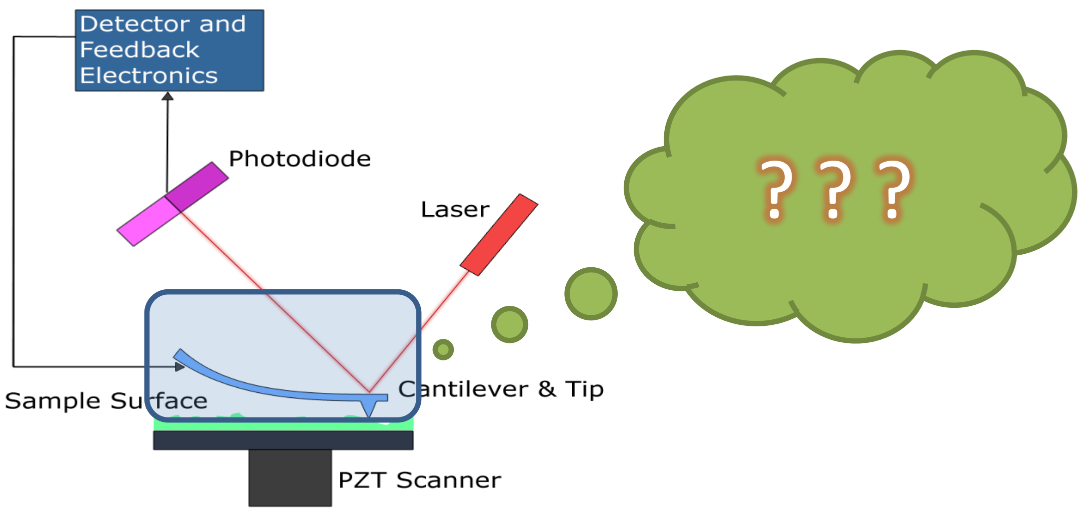
Atomic Force Microscopy

- Proven utility for Nanoscience
- Optical readout works well
- Free space optics:
  - cm-scale beam path
  - stray light
- Bulk external actuators
- Stability, vibration issues
- Precision is typically limited by optical readout noise
  - off-resonance
  - in low to modest Q situations (air, liquid)
- Bandwidth is limited by cantilever and readout



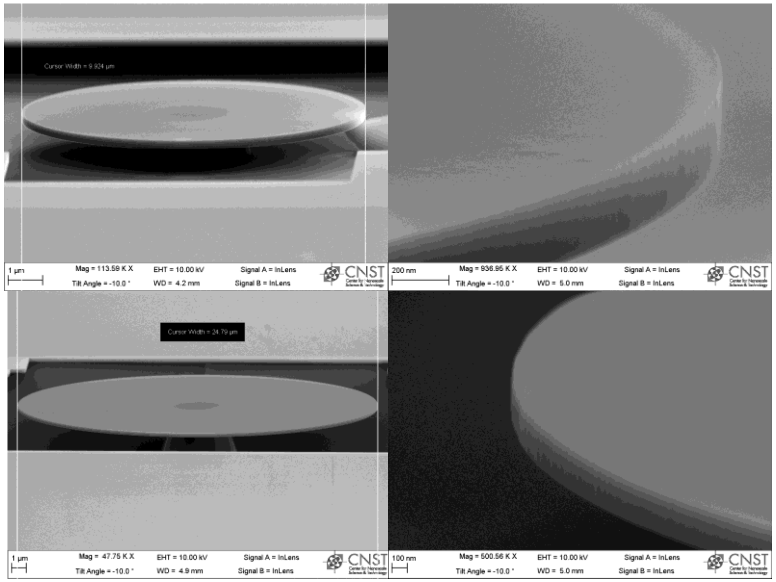
Motivation

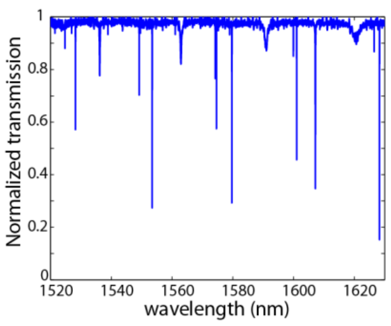
- Integrated Optical Sensing of Mechanical Motion
  - Optical Interferometric Readout
  - High Q and High Bandwidth Mechanical Probe
  - Internal MEMS Actuation
  - Fiber Based Excitation and Readout
  - Applications in Real Life Problems i.e. AFM

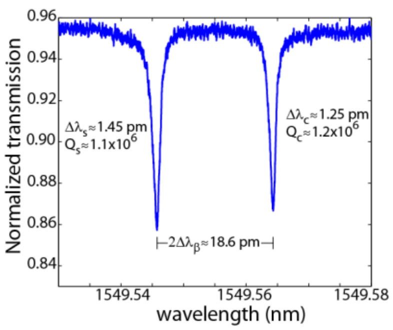


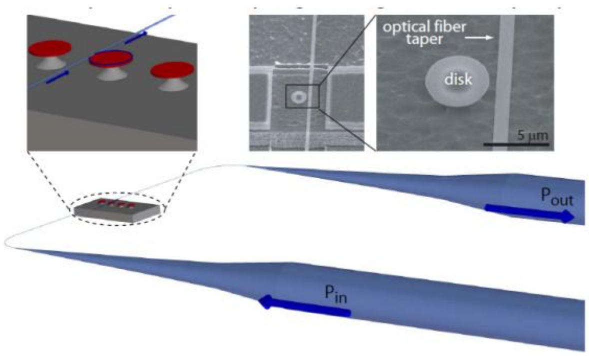
Nanophotonic Resonators

- Microtoroid ($Q\sim10^8$)
- Microdisk ($Q\sim10^6$)
  - 10 µm diameter Si disk $Q=1.2\times10^6$
  - 25 µm diameter SiN disk $Q=1.7\times10^6$
- Microring ($Q\sim10^6$)
  - 60 µm diameter SiN ring $Q=1\times10^6$
- Photonic Crystal ($Q\sim10^5$-10^6)
  - L3 Cavity $Q=5\times10^4$
  - MH Cavity $Q=2.9\times10^5$



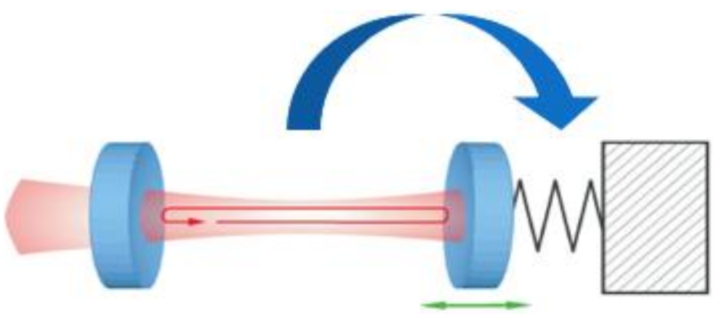




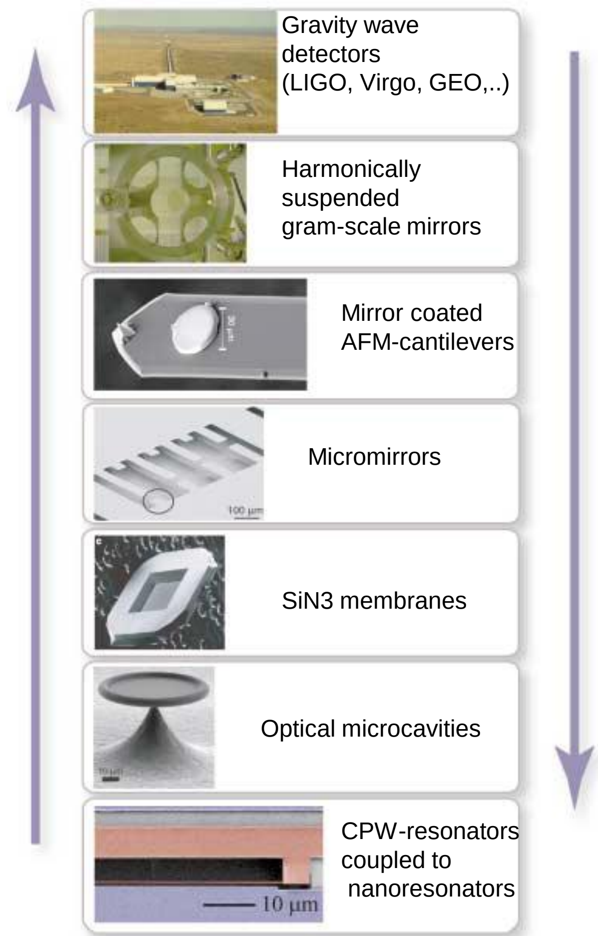


Cavity Optomechanics

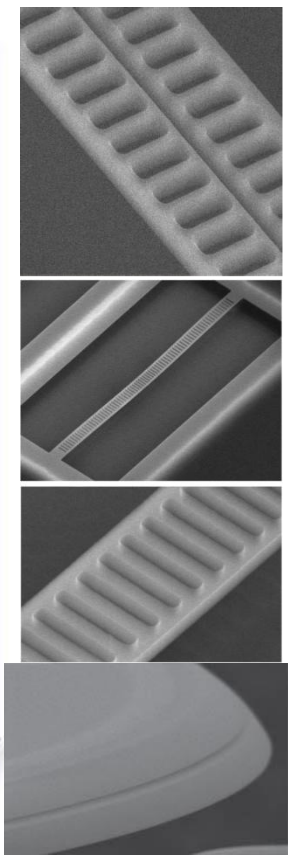
- Optical shot noise limited mechanical measurements with noise floors of order 10^{-18} m/Hz$^{1/2}$.
- Opto-mechanical cooling reduces thermal noise floor by orders of magnitude.
- Optically excited regenerative oscillation for precise mechanical frequency shift measurements.



Coupling of high Q mechanical and high Q optical modes



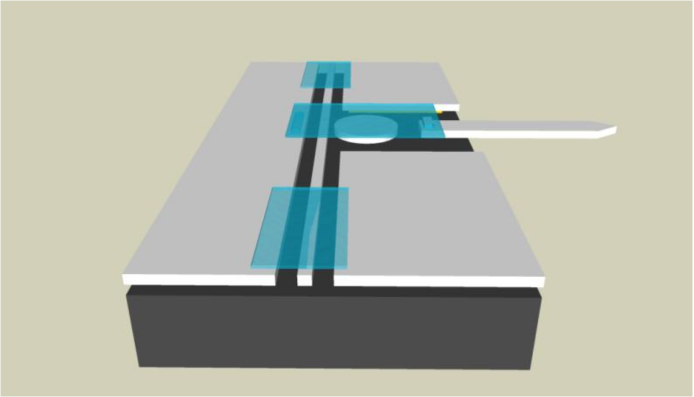
T. J. Kippenberg, Science (2008)

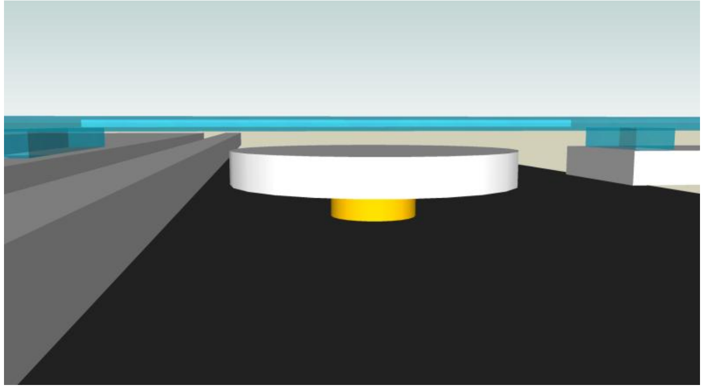


O. Painter's group

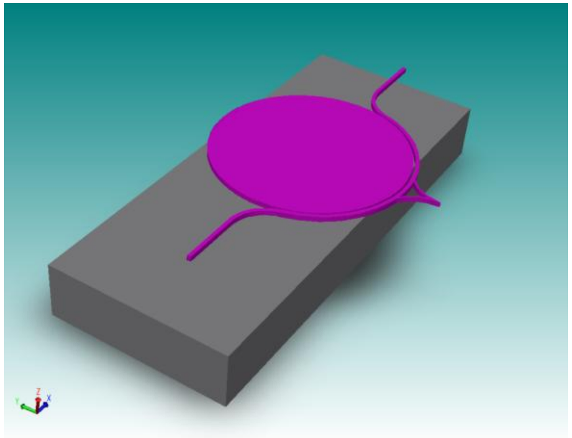
Integrated MEMS Tunable High Q Optical Cavity

- MEMS Actuated Mechanical Resonator
  - Single crystal Si, Si nitride
  - Electrostatic actuation for
    - Tuning
    - Positioning
- High Finesse Interferometry
  - Si Microdisk resonator (Q>1M)
  - Integrated optical excitation
- Evanescent Field Optical Coupling
- Independent Optimization of Optical and Mechanical Components

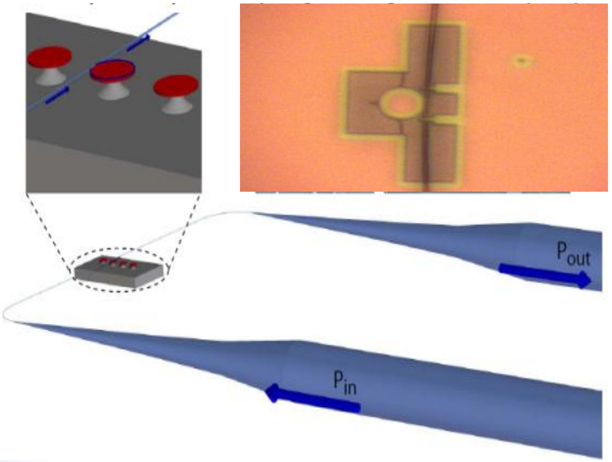


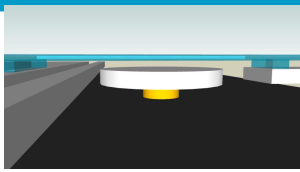


Simplified In-plane Opto-Mechanical Probe

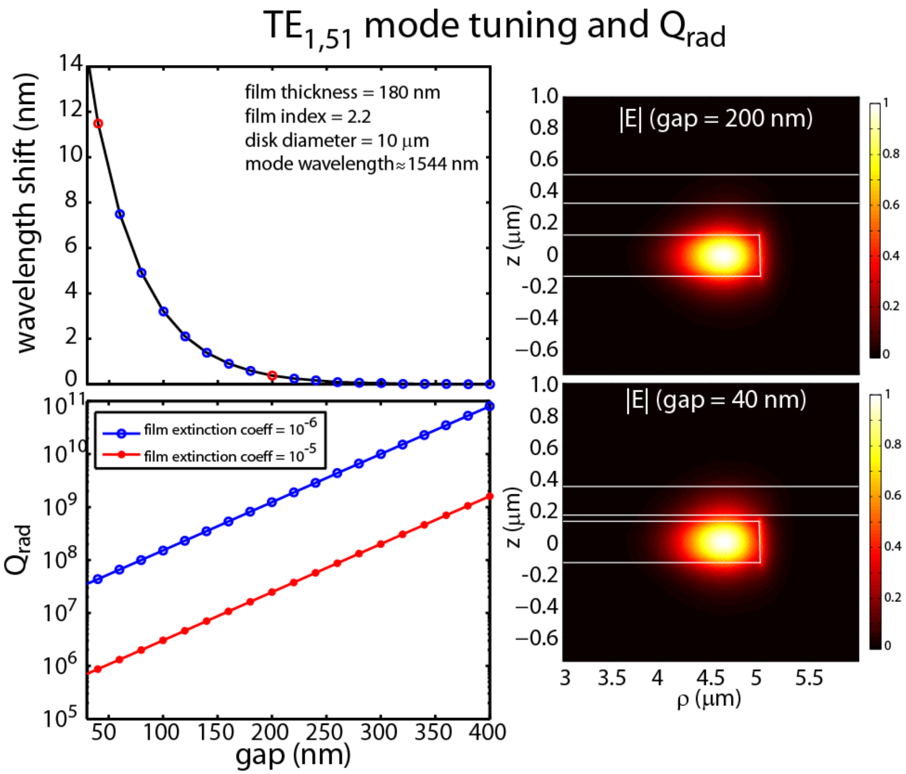


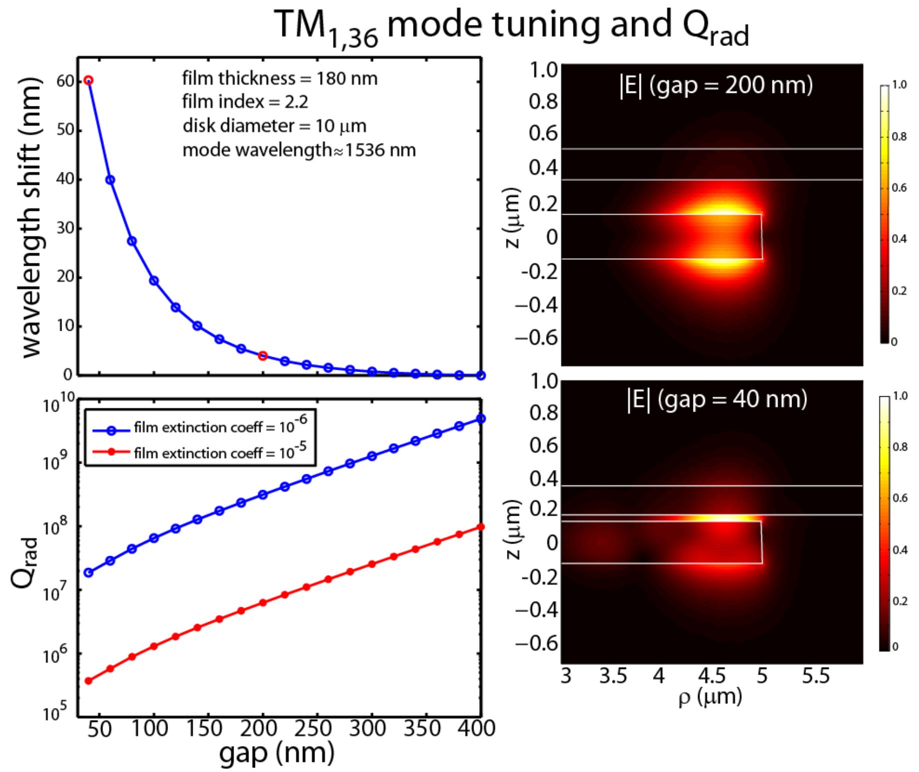
- Mechanical Resonator
  - Single crystal Si
  - Small, high bandwidth
- High Finesse Interferometry
  - Si Microdisk resonator
  - External excitation (tapered fiber)
- Evanescent Field Optical Coupling



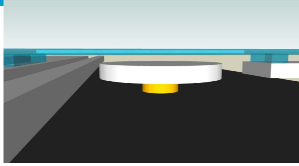


FEM Simulation





Device Design, Fabrication and Mechanical Testing

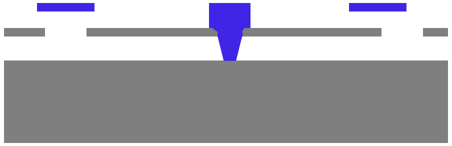


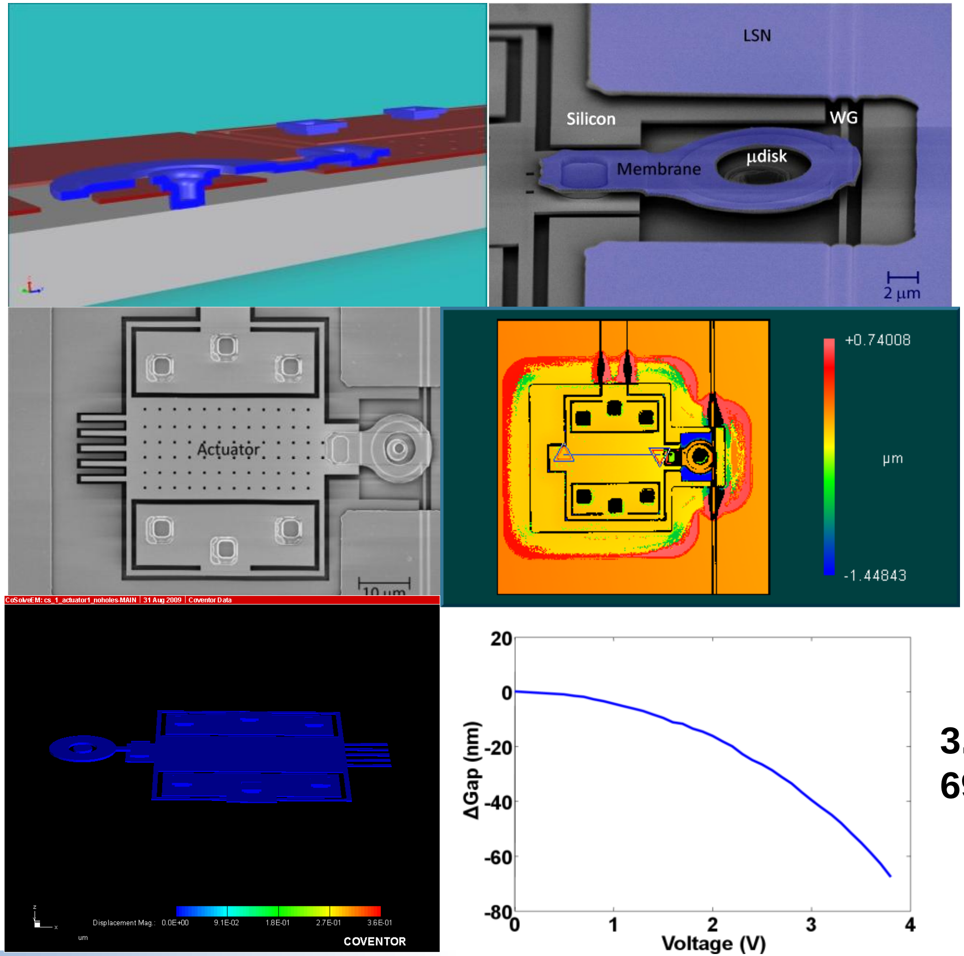
SOI: 260 nm Si, 1 µm Oxide

Si layer patterned with E-beam and dry etched

Si Dioxide deposited, patterned and etched

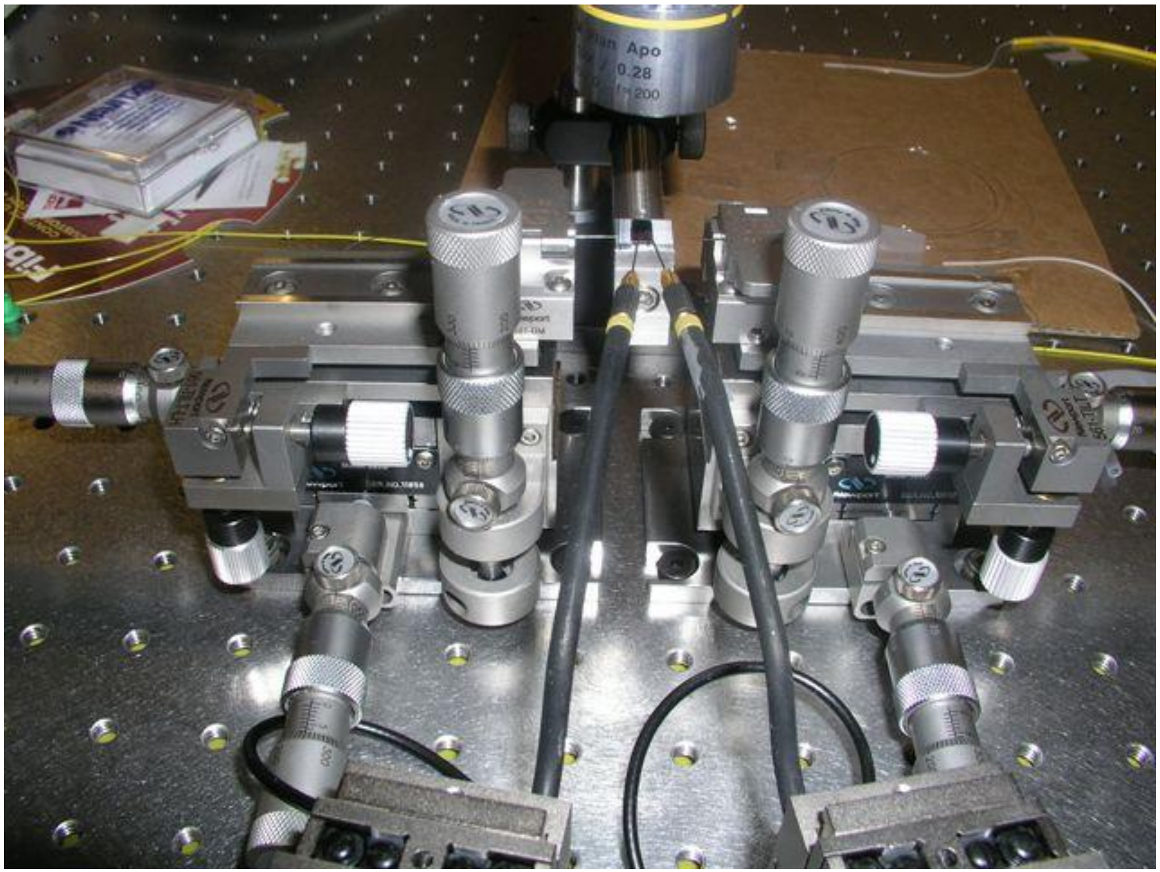
Si Nitride deposited, patterned and etched; Si Dioxide etched

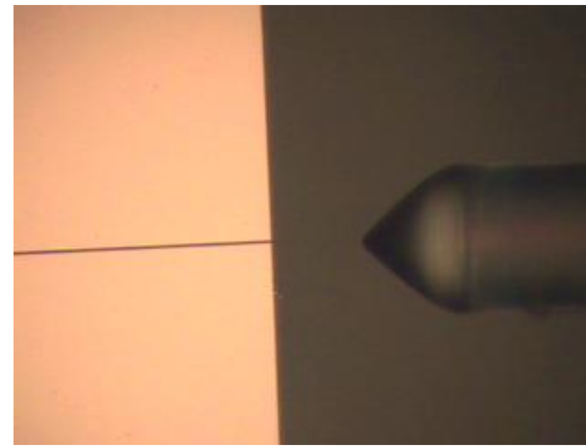


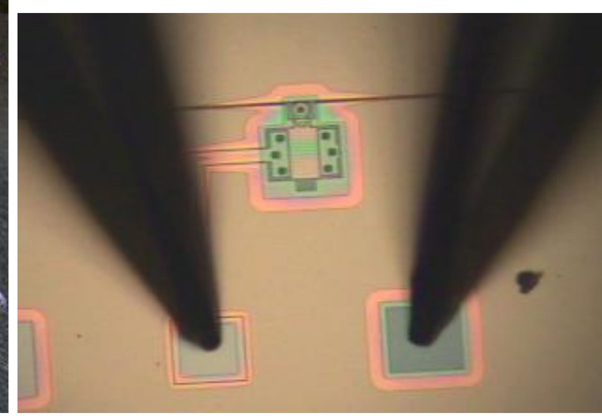


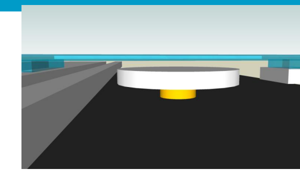
3.8V: 69 nm

Testing Setup



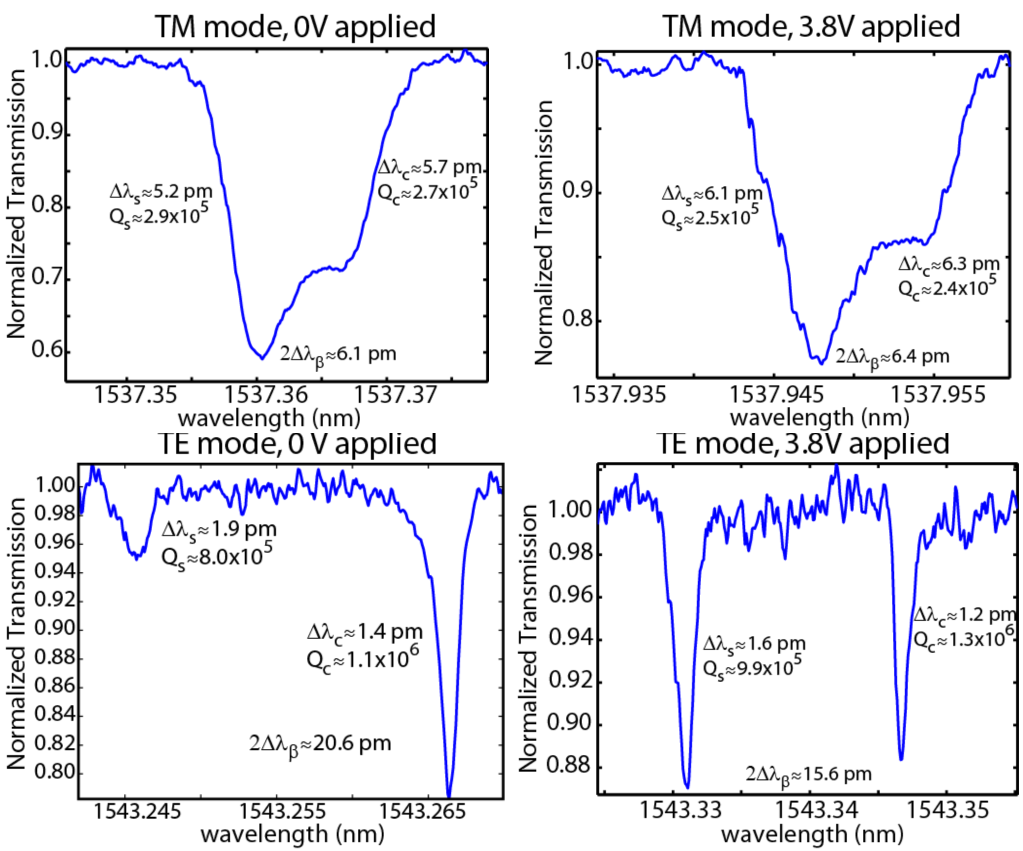




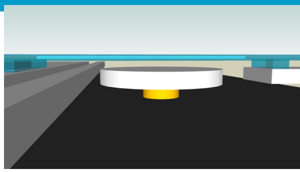


Experimental Results

- Resonant spectra at various gaps

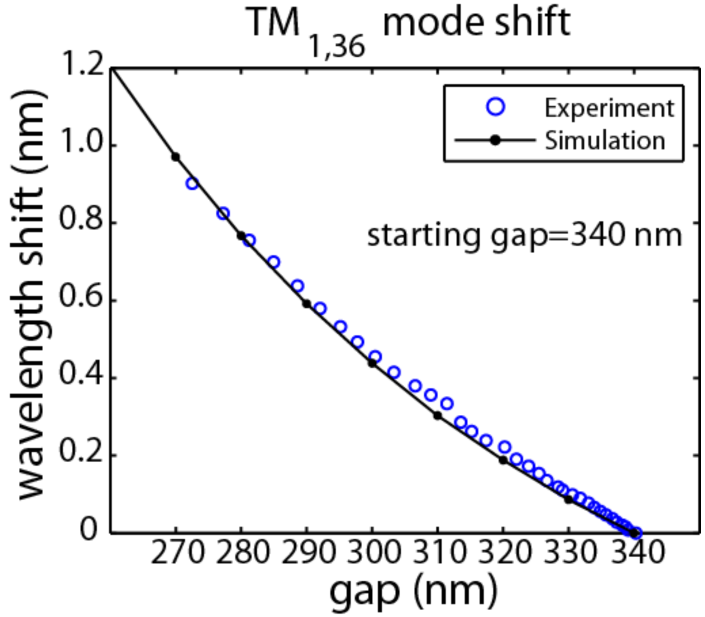


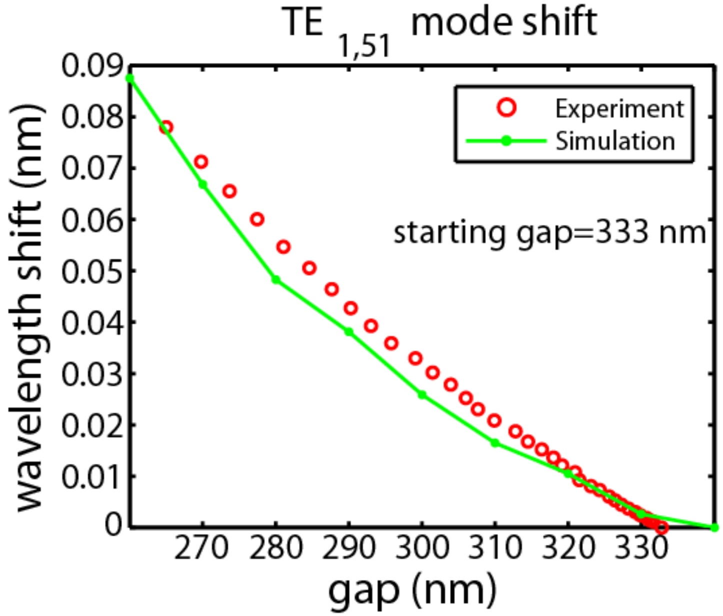
- **5.2 pm linewidth (TM, Q ~ 3.0×10^5)**
- **1.2 pm linewidth (TE, Q ~ 1.3×10^6)**
- **69 nm mechanical displacement**
- **No obvious optical Q degradation**



Experimental Results

- Resonant frequency tuning vs. gap change



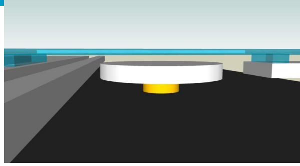


➢**Optical resonance tuning: ~ 150 linewidth (TM); ~ 50 linewidth (TE)**

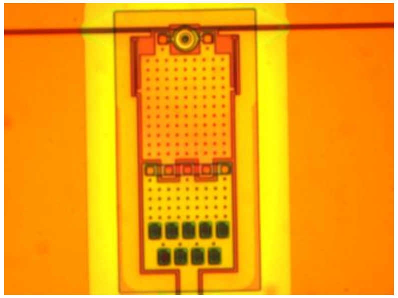
➢**Mechanical Displacment/resonance shift: 0.5 nm/linewidth (TM); 1.3 nm/linewidth (TE)**

➢**Implication for displacement sensing: 0.5 pm sensitivity assuming a 1000 SNR**

Integrated MEMS Tunable Cavity Summary



- Optomechanical Transduction
  - **Optical Cavity Linewidth: 1.2 pm (TE, Q~1.3x10^{6})**
  - **Optical resonance tuning: ~ 150 linewidth (TM)**
  - **Mechanical Displacement/resonance shift: ~0.5 nm/linewidth shift (TM)**
  - **Implication for displacement sensing: < 0.5 pm sensitivity**



New Design

Optical resonance tuning: 15 nm ~ 750 linewidth (TM)