Understanding EUV Resist Performance Using Scanning Probe Microscopy

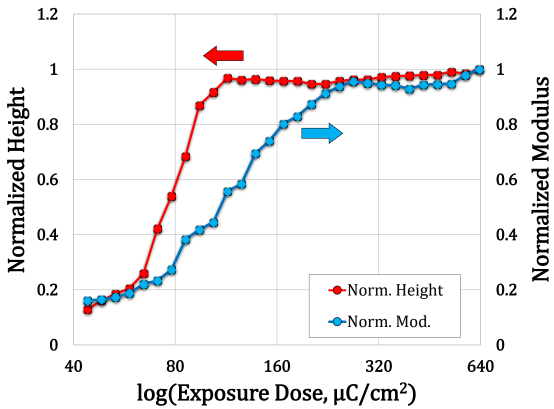
Paul Ashby
Staff Scientist
Imaging and Manipulation Facility
Molecular Foundry

BERKELEY LAB

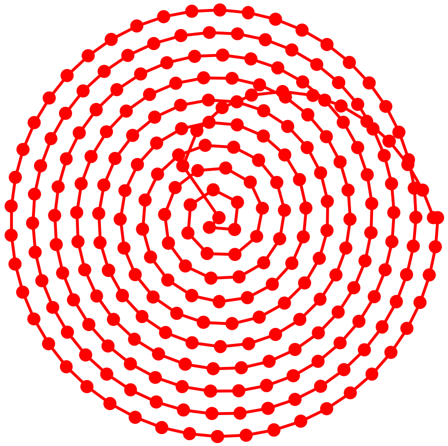
MOLECULAR FOUNDRY

Outline

EUV resist design and characterization



High speed Spiral Scan AFM



Encased Cantilevers for In-situ AFM

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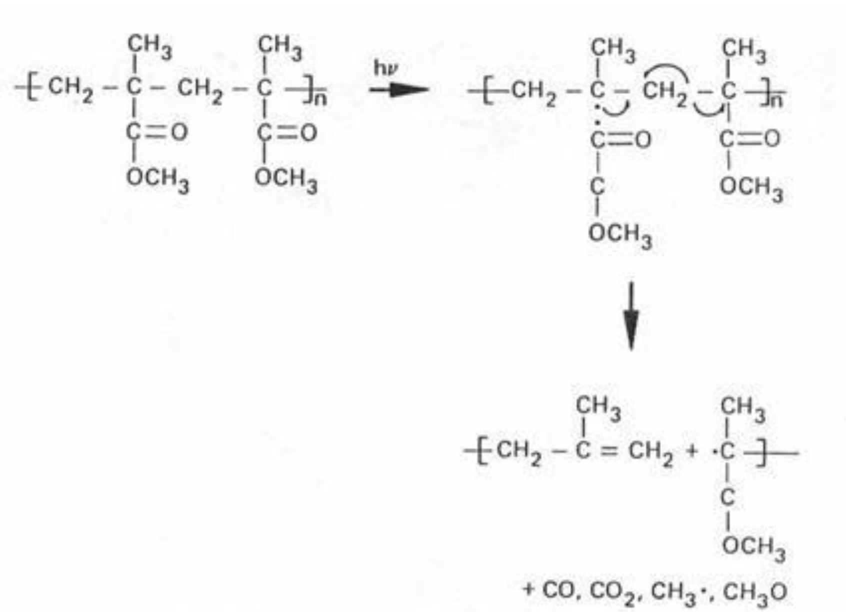
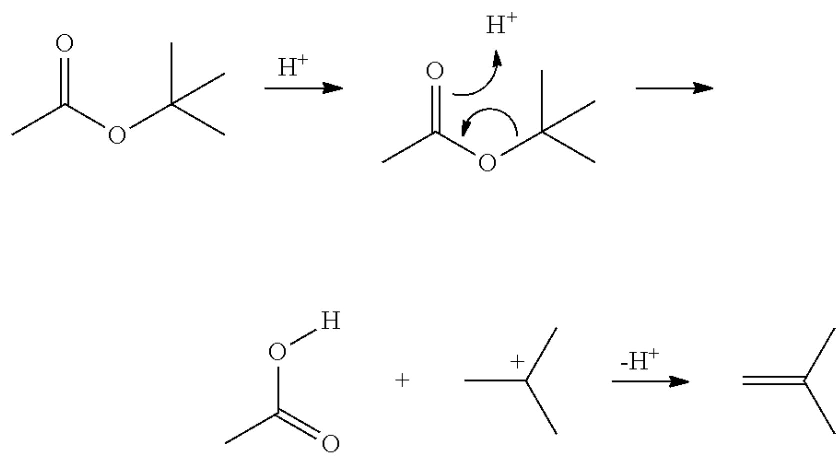
Chemical Contrast Mechanisms

Entropic



Enthalpic



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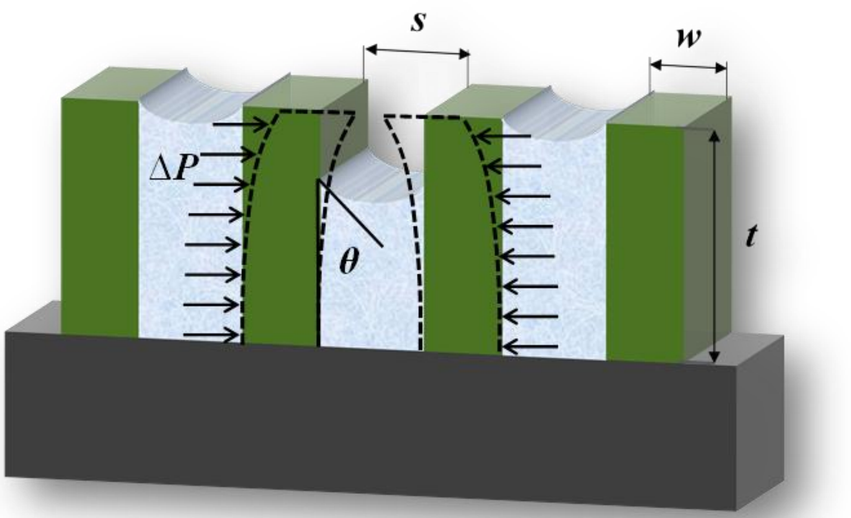
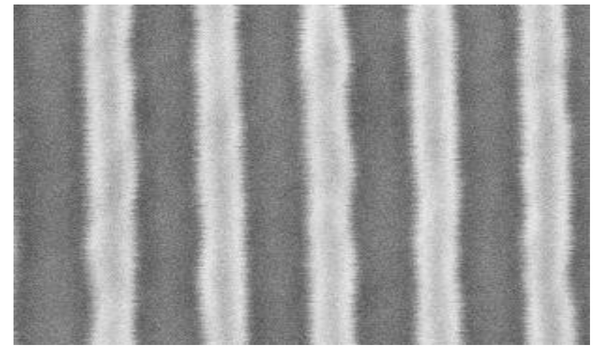
Factors limiting resist performance

- Pattern Collapse
- Swelling
- Poor Line Edge Roughness

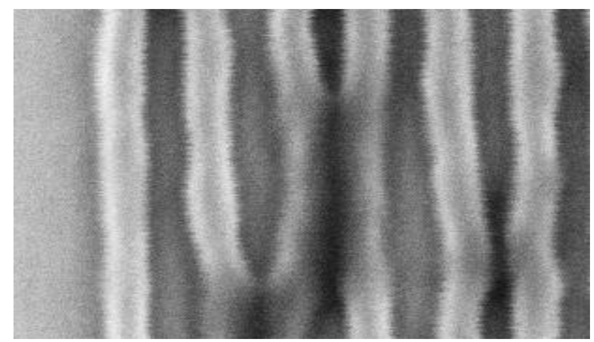


Capillary Induced
Pattern Collapse

60 pitch



48 pitch



$$\frac{E}{\gamma} \le \frac{8}{w_s} A_l^3 \left(3A_s \cos\theta + \sin\theta\right)$$

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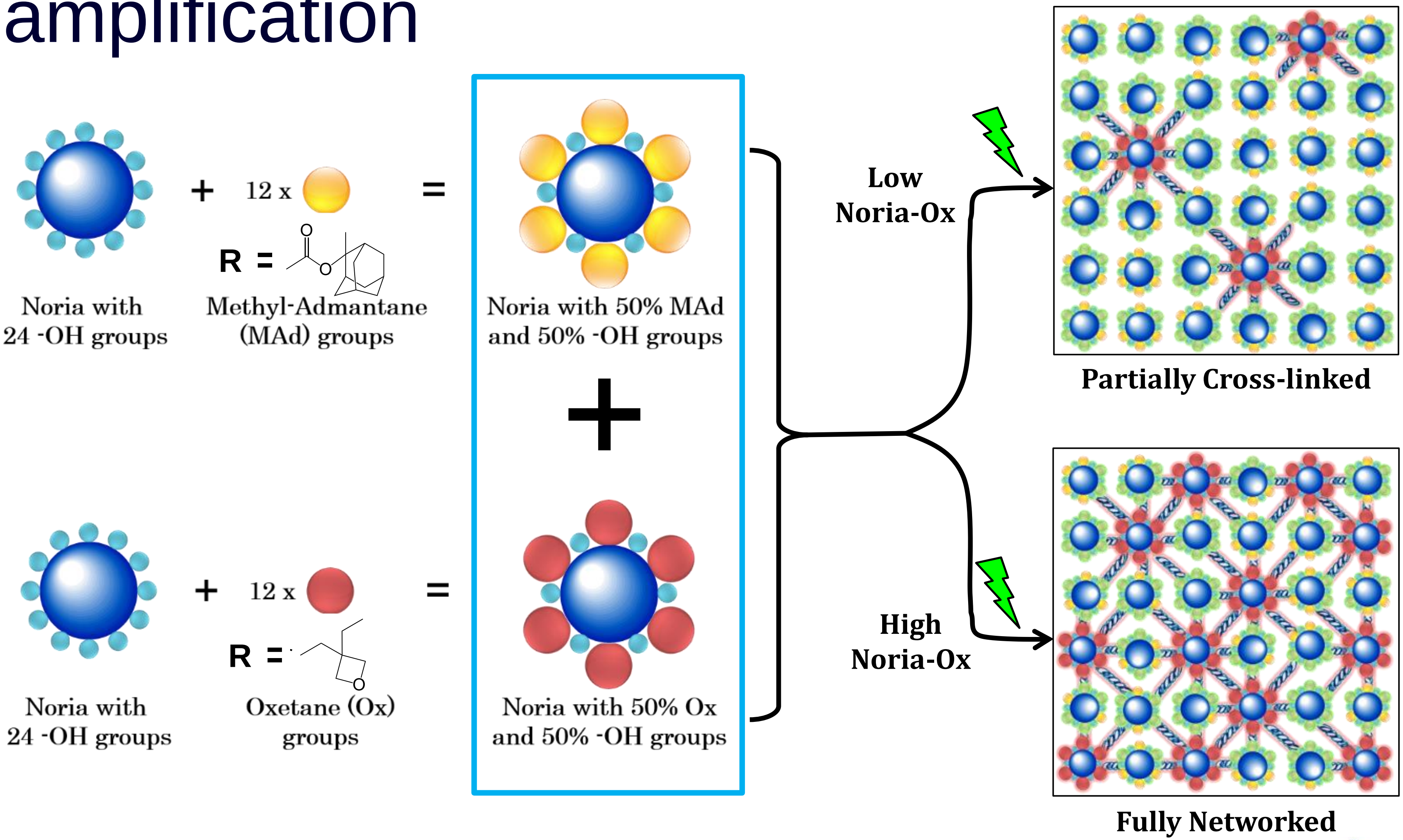
Combining cross-linking and chemical amplification



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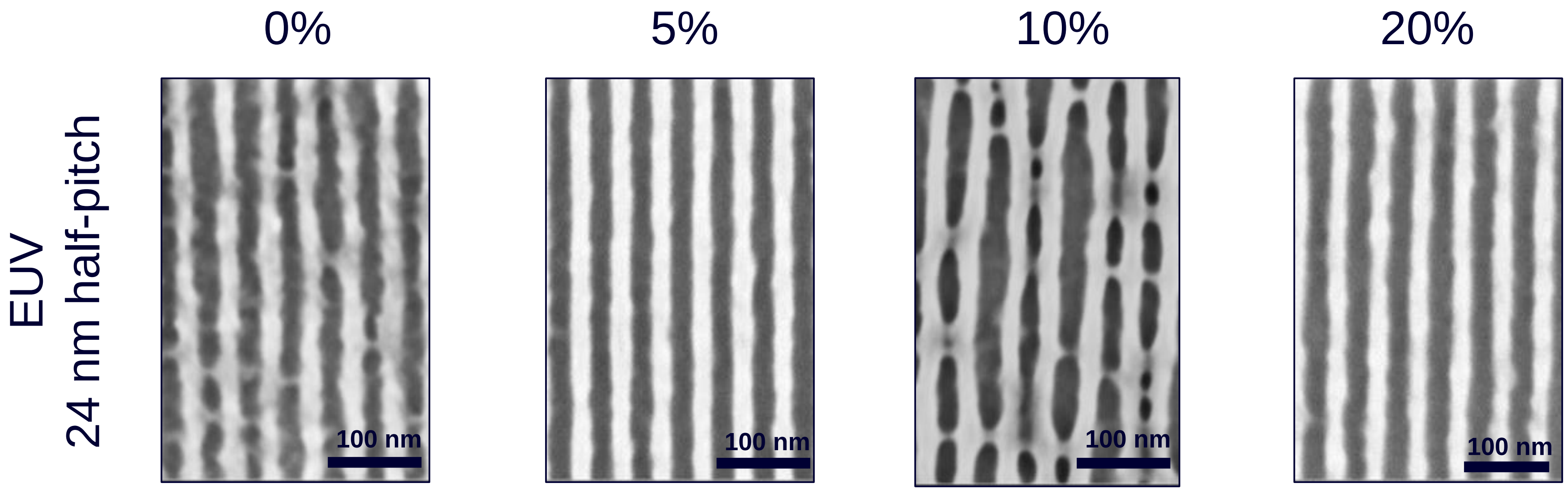
Cross-linking resist performance



5% oxetane cross-linkers in the resist solution patterns to higher resolution with lower line edge roughness.

Negative tone development using n-butyl acetate.

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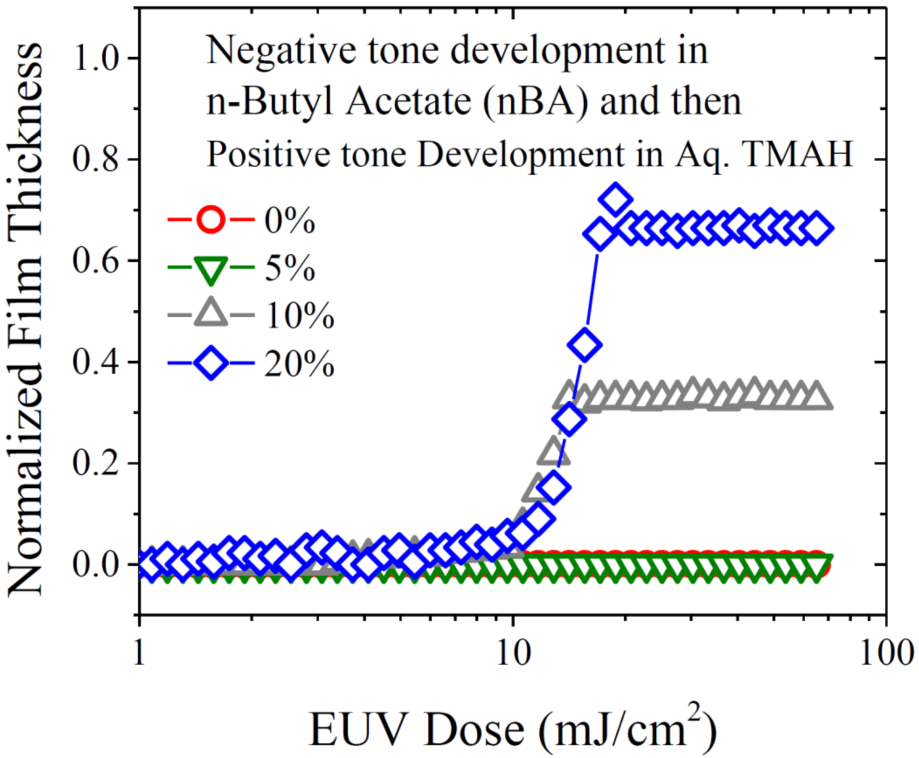
Best performer not highly cross-linked

Double development



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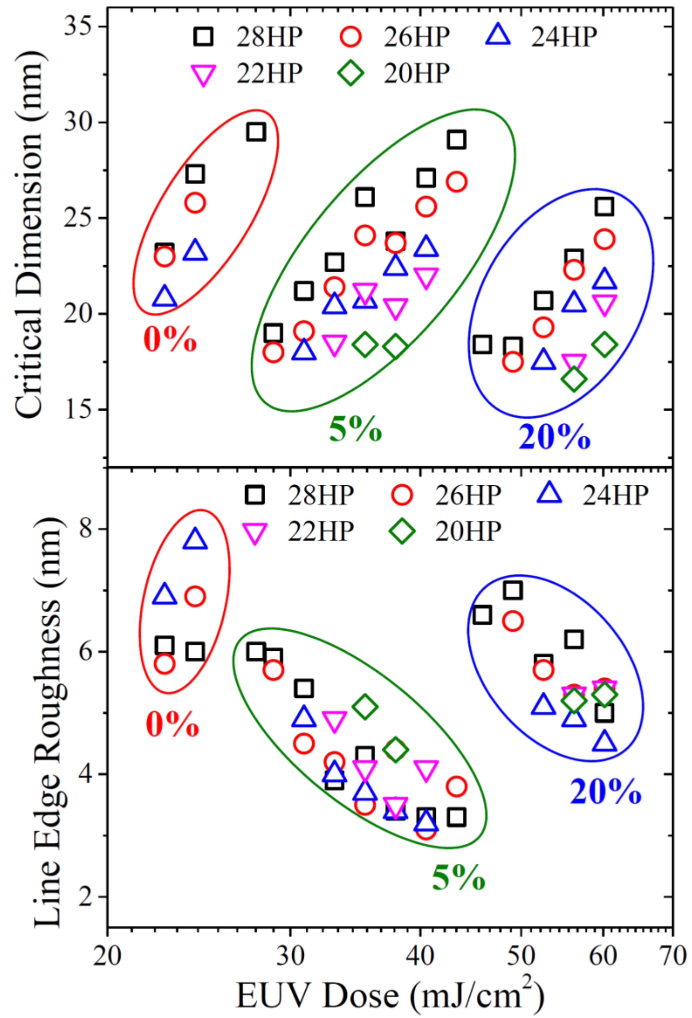
Improved process window



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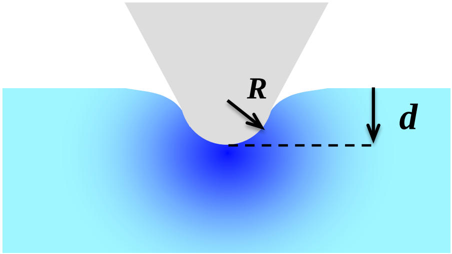
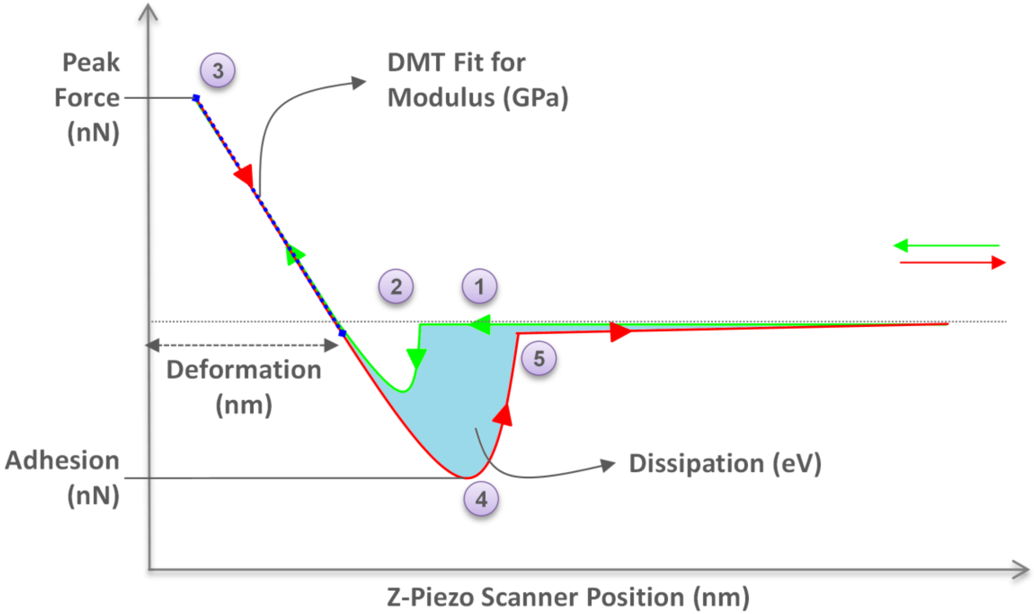
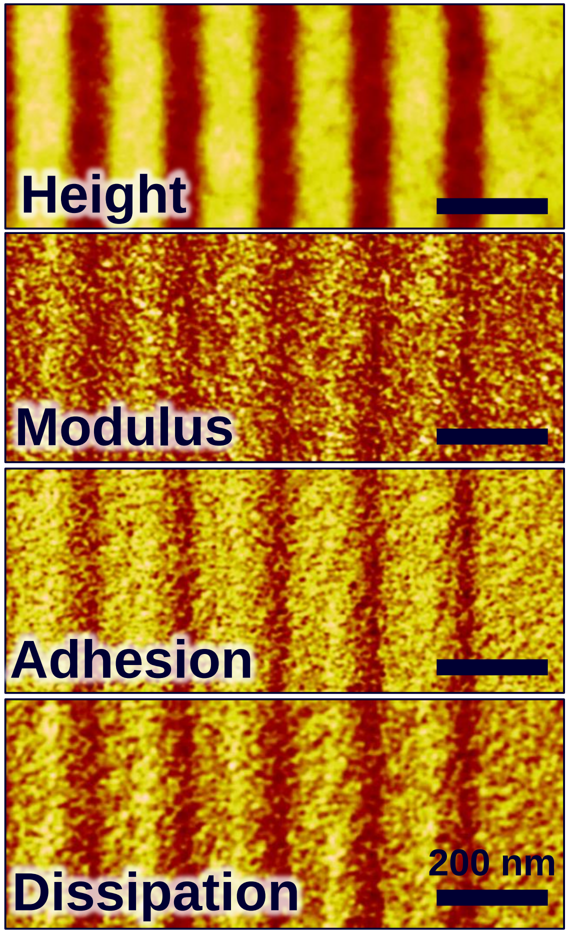
Nanomechanical mapping

$$F_{tip} = \frac{4}{3} E_r \sqrt{Rd^3} + F_{adh} = kx$$



PeakForce™ AFM





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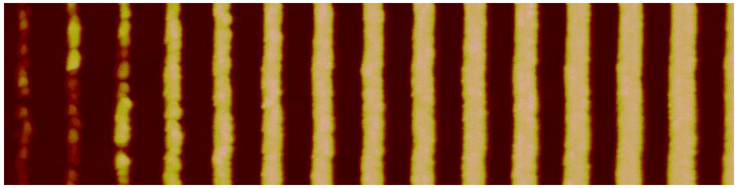
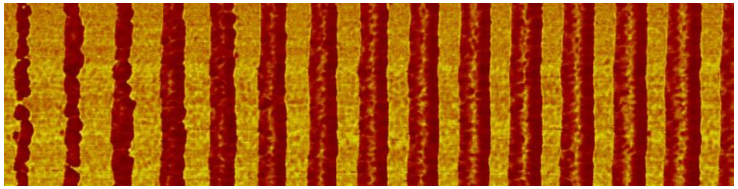
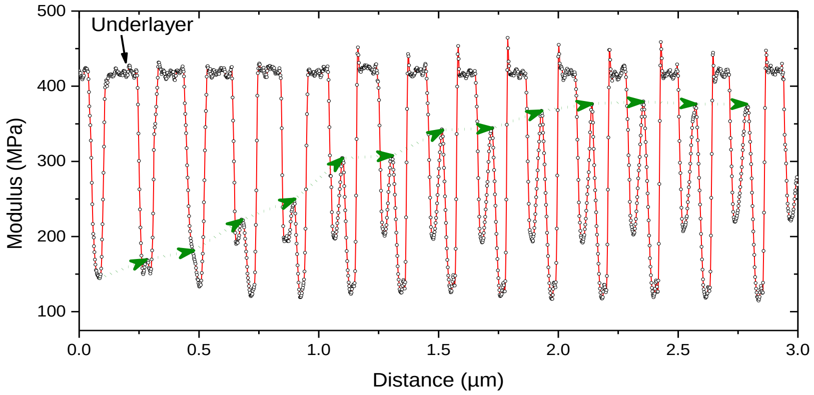
Modulus measures chemical change

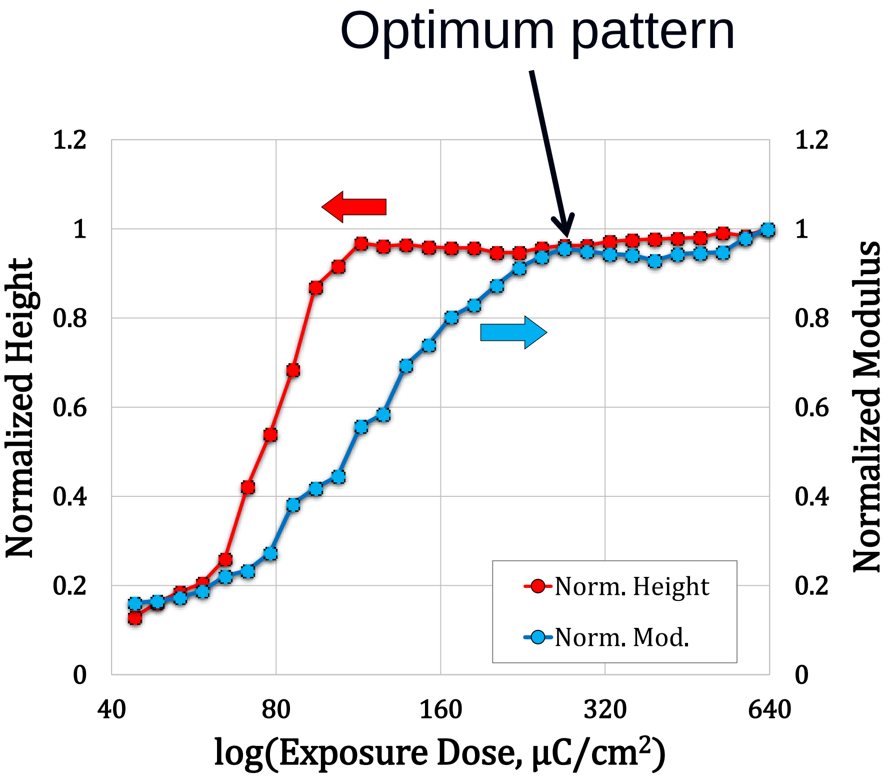
Height



Modulus







Modulus shows chemistry through dose past full thickness and is a good nanoscale measure of chemical change.

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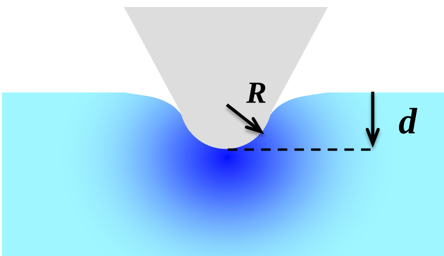
Acknowledgements

Novel EUV Resist Material and Mechanical Characterization

$$F_{tip} = \frac{4}{3} E_r \sqrt{R d^3} + F_{adh} = kx$$



Prashant Kulshreshtha (Molecular Foundry)
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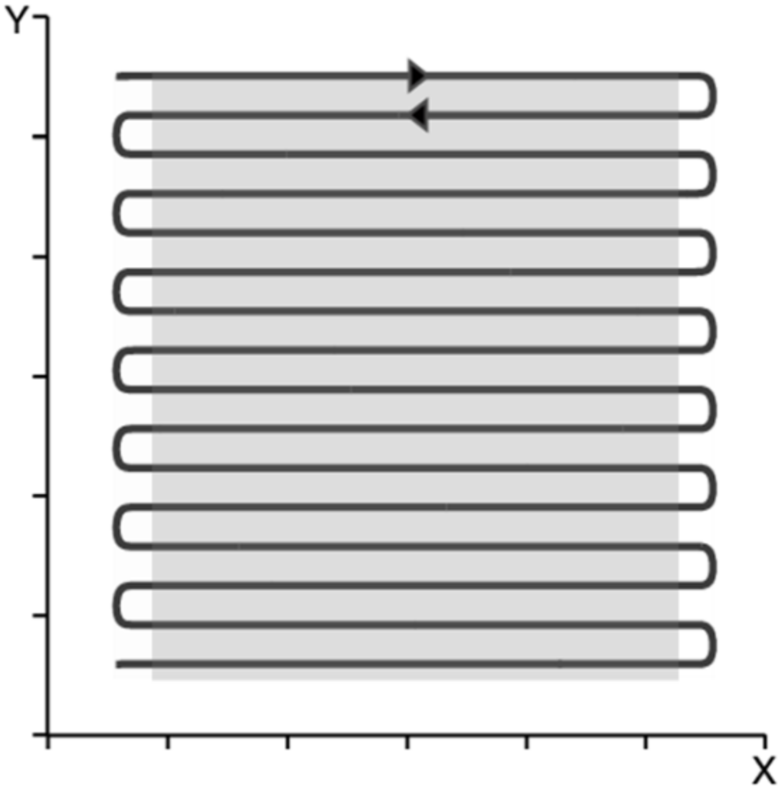
Kulshreshtha et. al., Nanotechnology 25 315301 (2014)
doi:10.1088/0957-4484/25/31/315301

Kulshreshtha et. al., SPIE Advances in Patterning Materials and Processes XXXII, (2015), doi:10.1117/12.2086045.

Rasterkraftmikroskopie



Raster scanning saved bandwidth.

Requires constant velocity and high acceleration at the turnarounds.

Throw away half the data per image.

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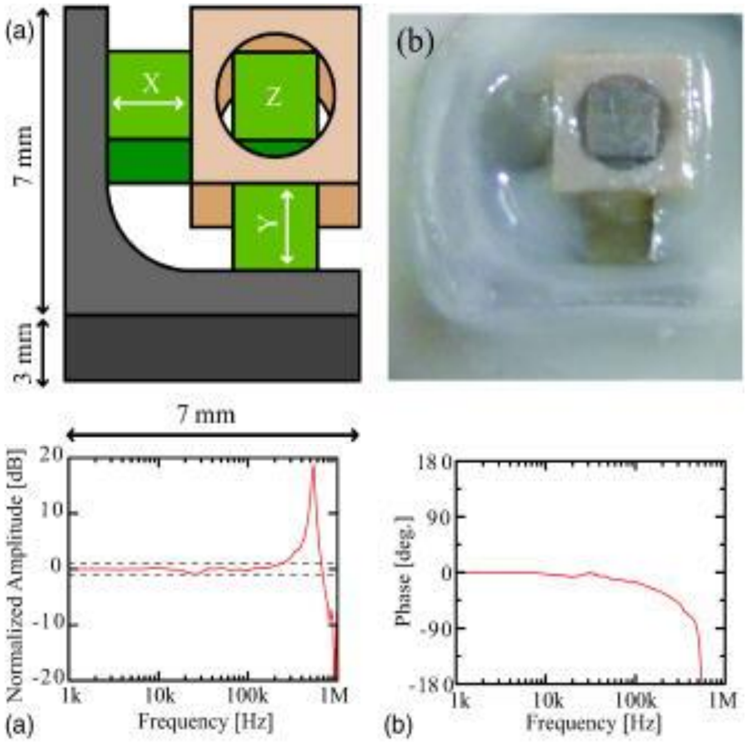
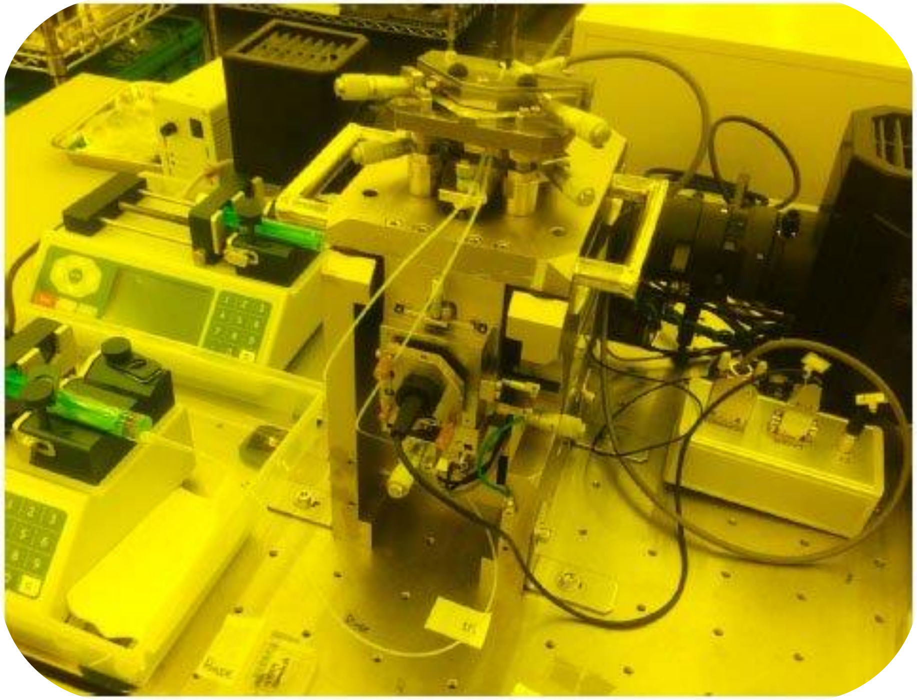
High Speed AFM



Ando et. al., APL, 92, 243119 (2008)



EUVL Infrastructure Development Ctr., Inc.

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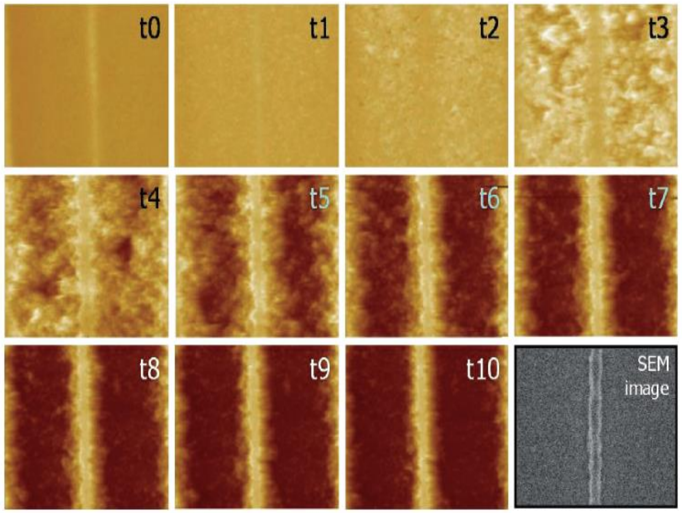
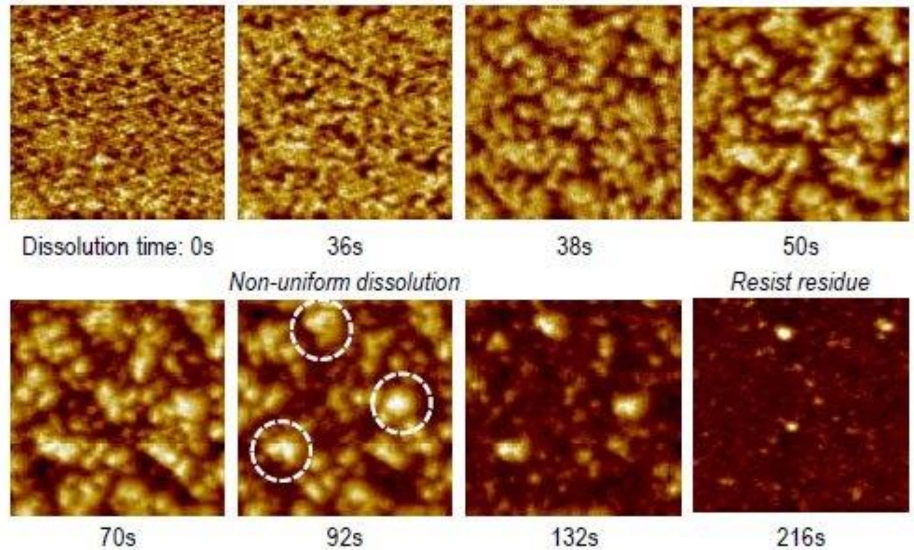
Resist Development by HSAFM



Toshiro Itani and Julius Joseph Santillan,
Applied Physics Express, 3, 061601 (2010)



Toshiro Itani and Julius Joseph Santillan,
Advanced Lithography 2018 DOI:10.1117/12.2294585

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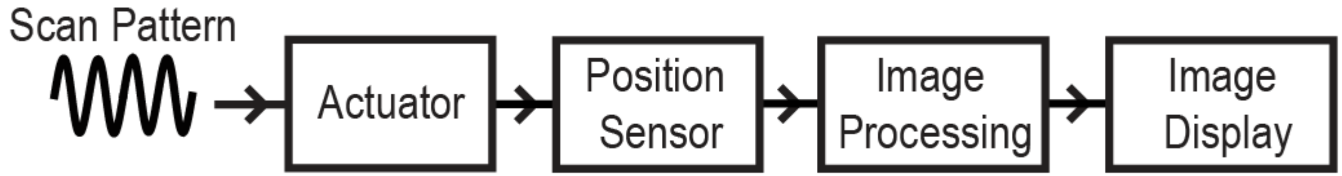
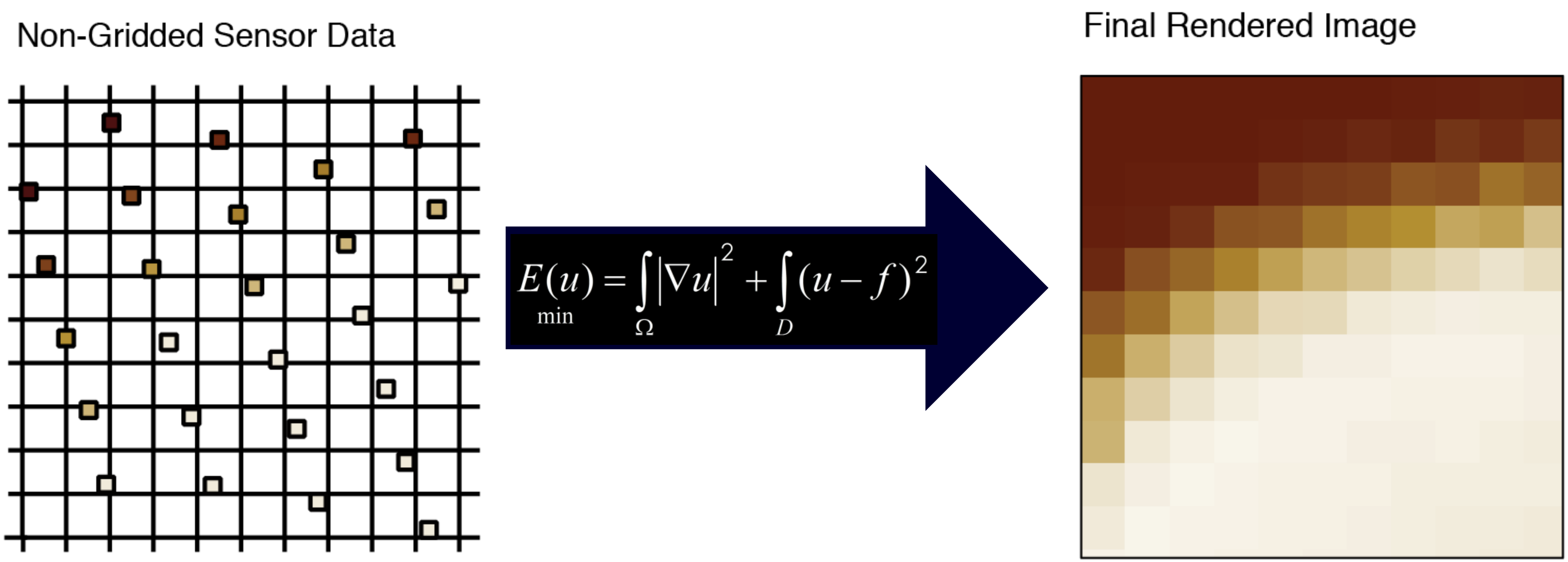
Breaking the paradigm

Sensor Inpainting





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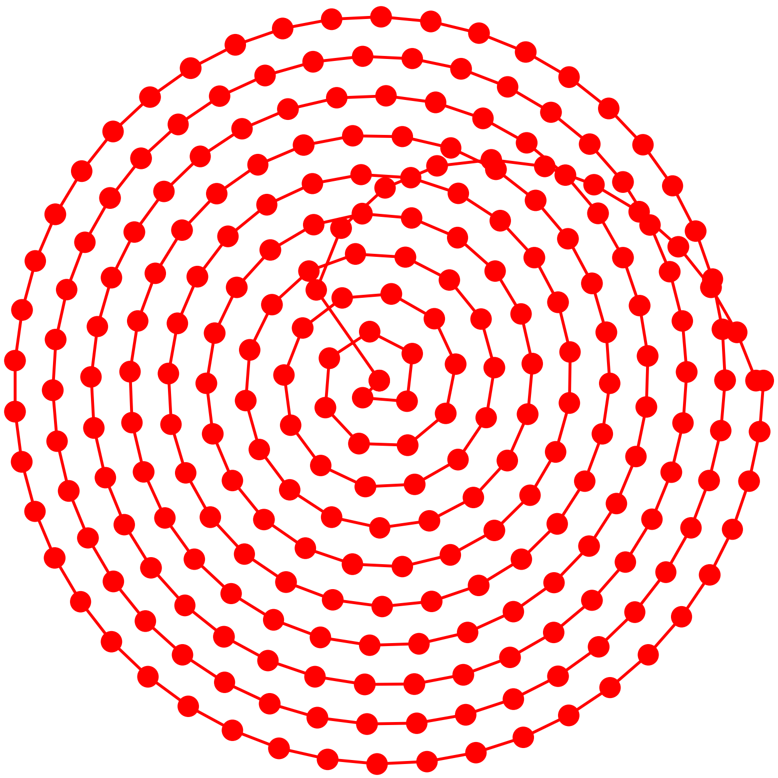
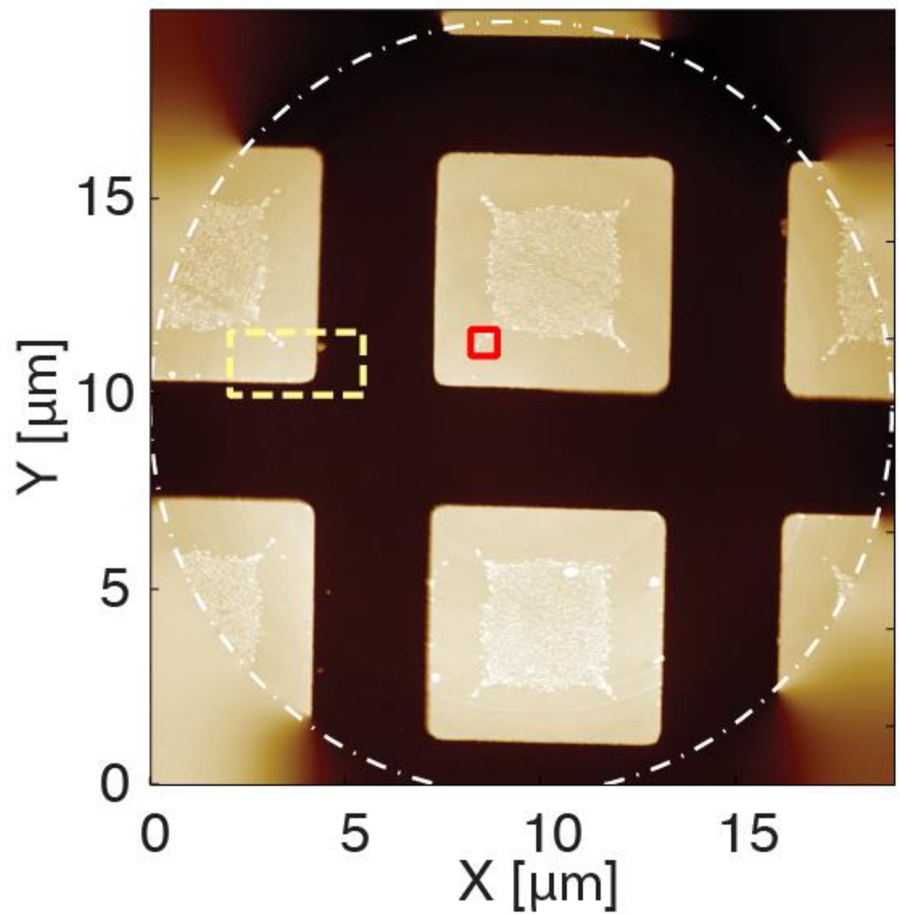
Spiral scanning





Utilizes almost 100% of the scan time.

All scan lines are in same direction.

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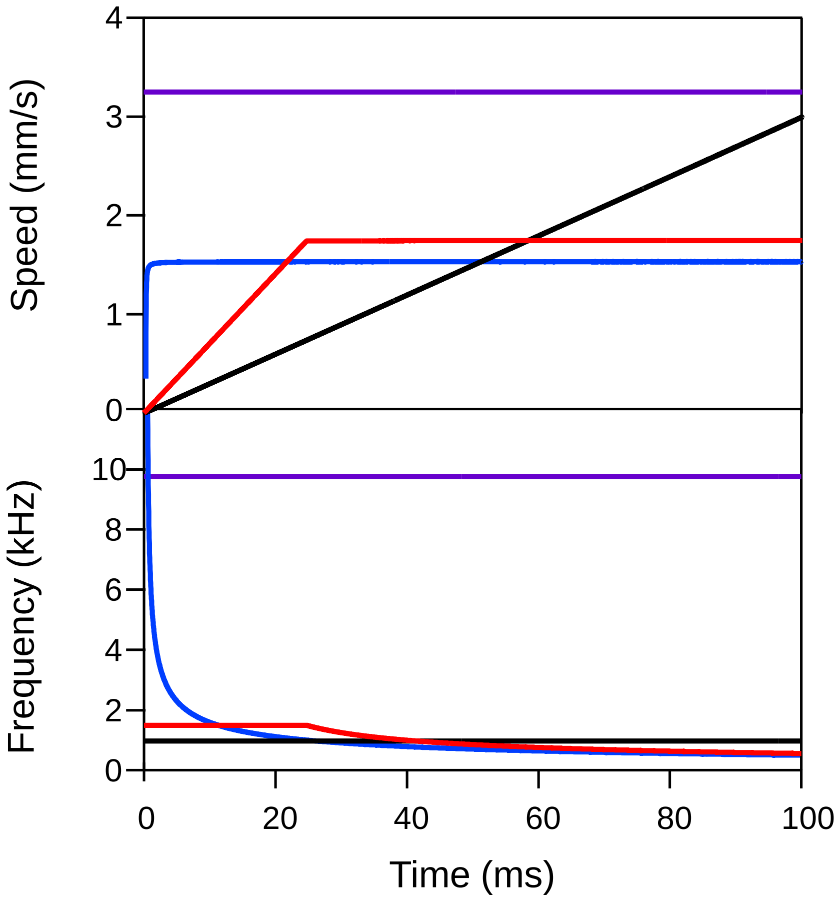
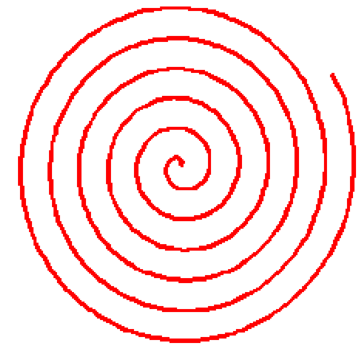
The Optimal Spiral

Spiral Scans vs Raster scan



Archimedean Spiral (even spacing)

$$r \propto \theta$$



Constant Linear Velocity

$$\theta \propto \sqrt{t}$$

Constant Angular Velocity

$$\theta \propto t$$

Optimal Spiral

Optimal Spiral is safest and fastest!

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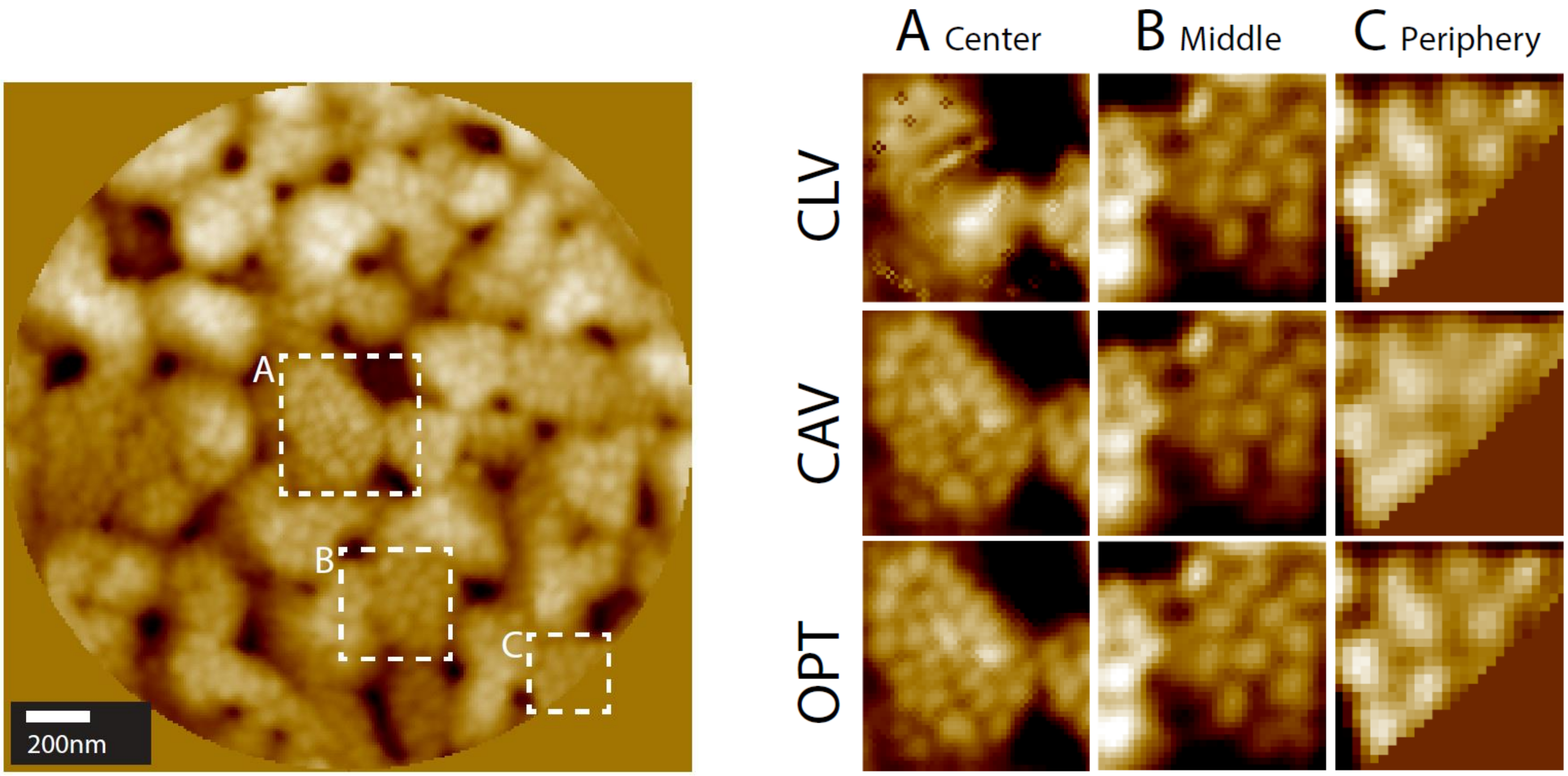
Spiral Comparison



Optimal spiral has highest fidelity over the whole image.

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Alternate Waveform Comparison

	Raster	Spirograph	Lissajous	CLV	CAV	OPT
Maximum Angular Frequency	> 9.0	3.1	2.0	>50	1.0	2.1
Angular frequency Variation	>1.5	0	0	1.2	0	0.5
Speed	2.3	3.1	4.9	1.0	2.0	~1.1
Average Sample Density	0.4	1.0	1.0	0.95	0.95	0.95
Maximum Sample Density	1	22	49	1	39	19
Sample Density Variation	0	0.3	0.5	0	0.39	0.04
Data Prioritizes Center	---	---	×	---	✓	✓
Adjacent Scan Lines are similar	✓	×	×	✓	✓	✓

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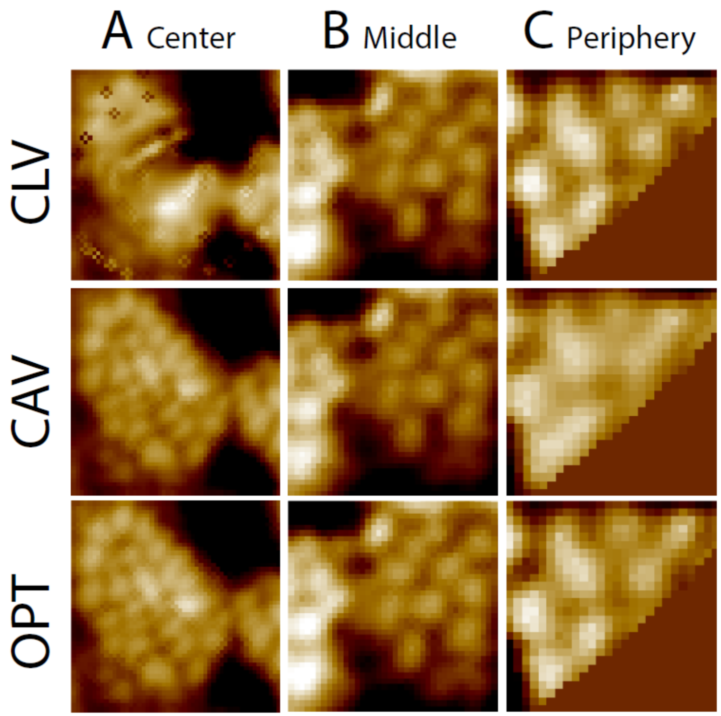
Acknowledgements

High speed Spiral Scan AFM



Dominik Ziegler (Molecular Foundry)
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Andreas Amrein (ETH Zurich)

Ziegler, et. al., Nanotechnology, v24, 335703, 2013

Ziegler, et. al., IEEE Mechatronics, v22, p381-391, 2016.

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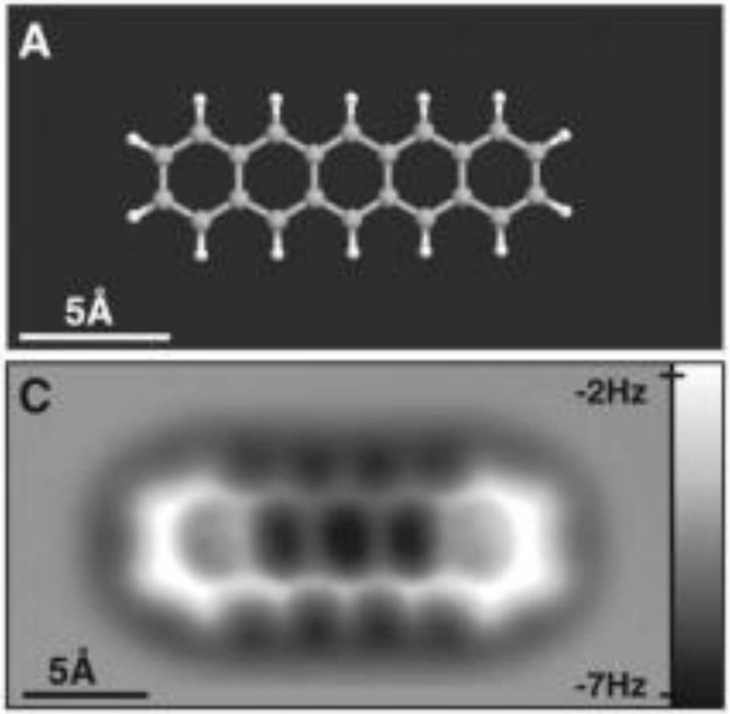
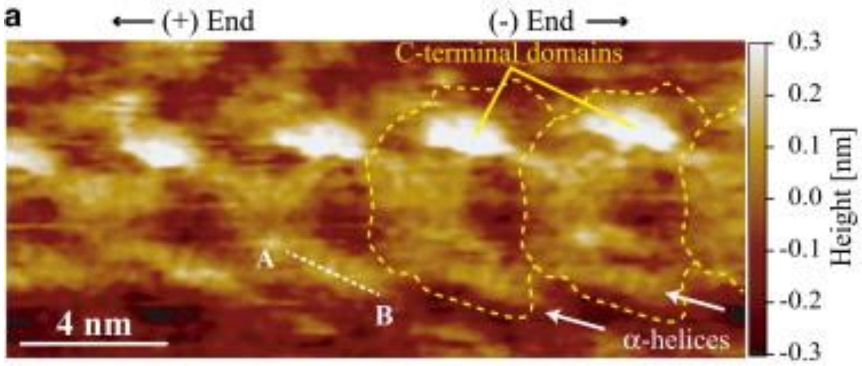
Liquid Compromises Resolution



Pentacene
Gross, et. al. *Science* v325 p1110 (2009)



Tubulin filament
Fukuma, et. al., *Biophysical Journal* v101 p1270 (2011)

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Low Force Noise Cantilevers

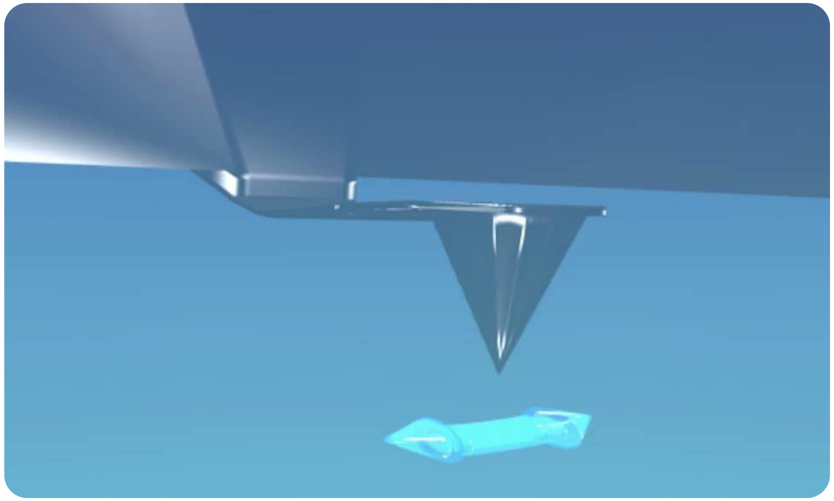
$$F_n = \sqrt{4k_BTb}$$

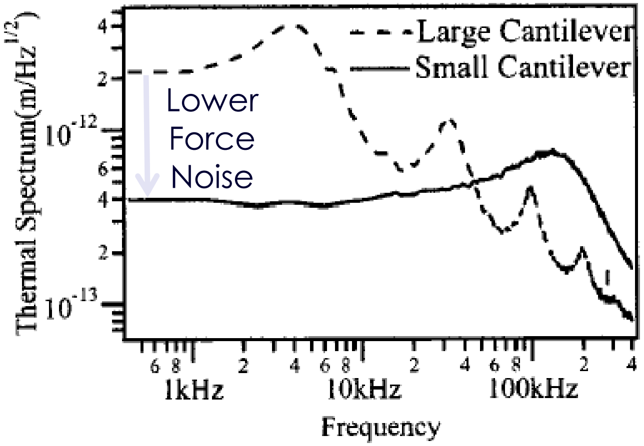
$$b = 6\pi R\eta$$

Size of object — Viscosity

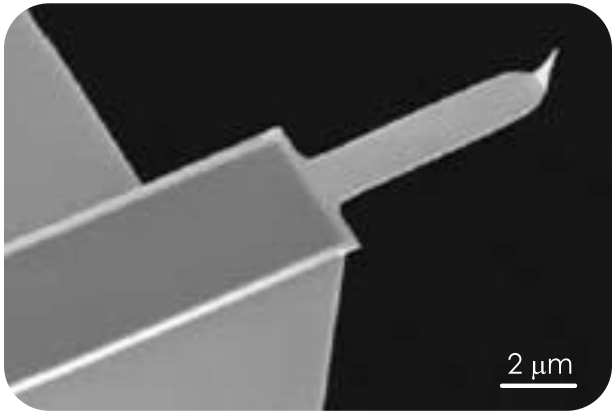
F_n=7fN/√Hz

Laser Tweezers





Viani et. al. *JAP* v86 p2258 (1999)



Olympus BioleverFAST

Force Noise
F_n=23fN/√Hz

Requires high NA instrument

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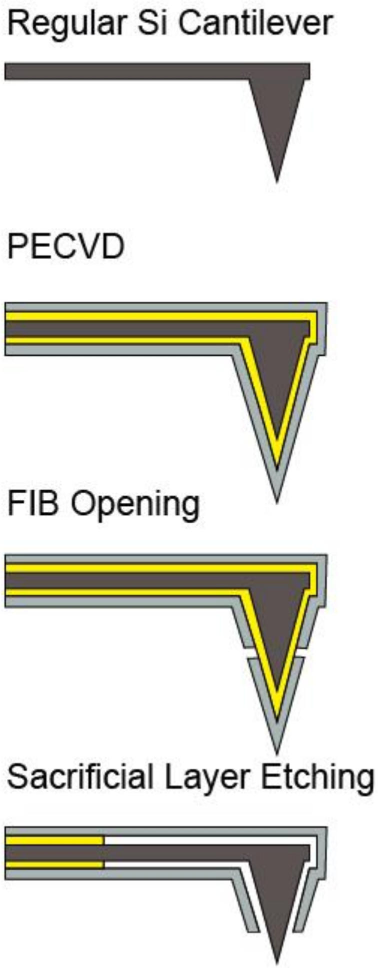
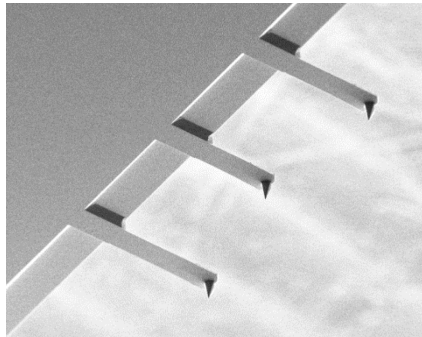
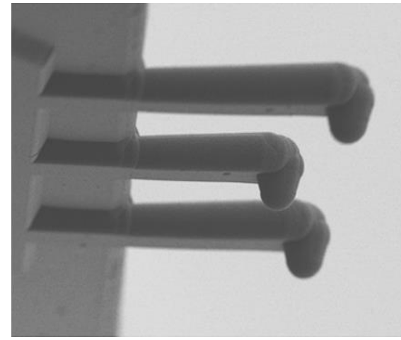
Encased Cantilevers

Changing η

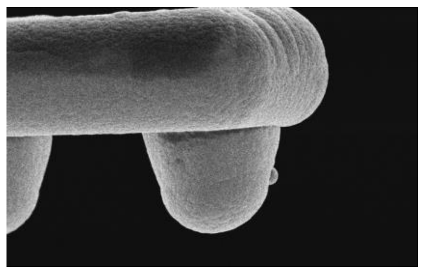
Encased Cantilever Fabrication

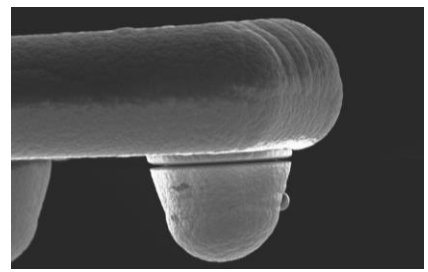




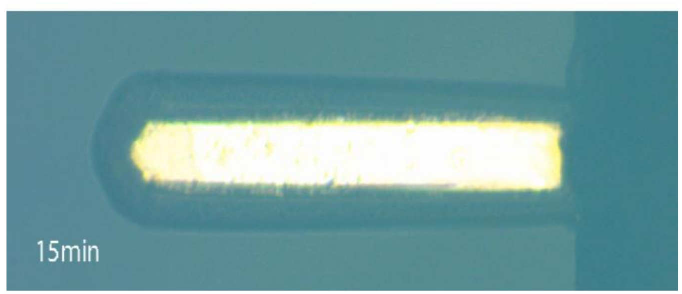


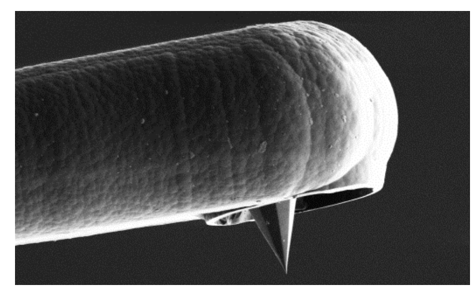
125 μm long
30 μm wide
40 N/m, 300 kHz,
Q~500
25 fN/√Hz





20 μm long
10 μm wide
1 N/m, 1 MHz,
Q~200
3.5 fN/√Hz





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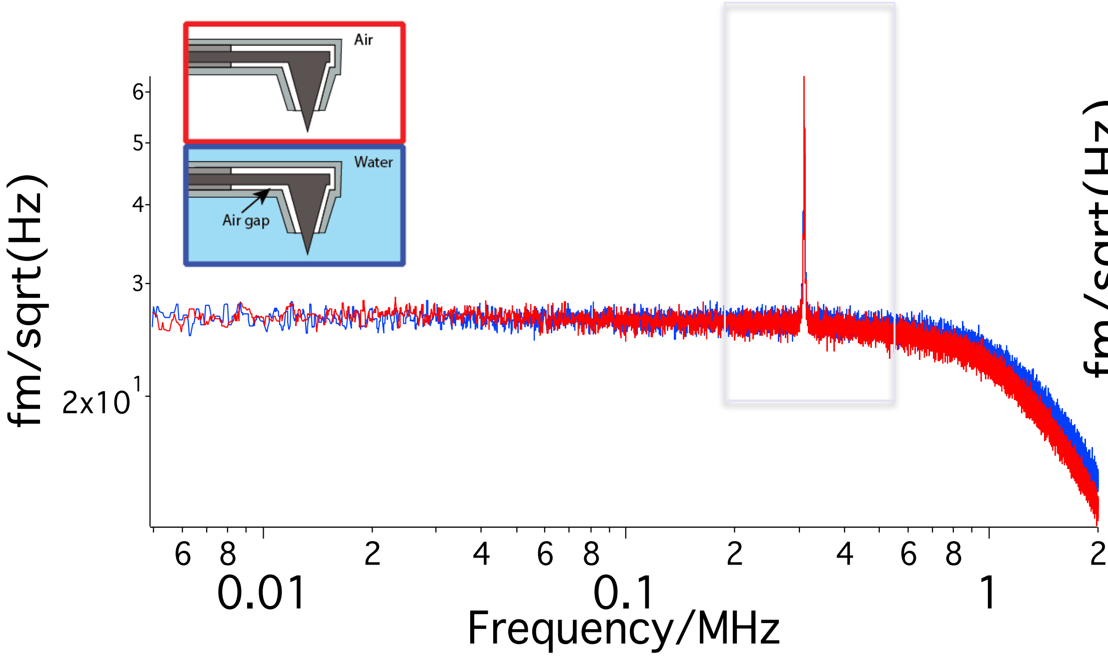
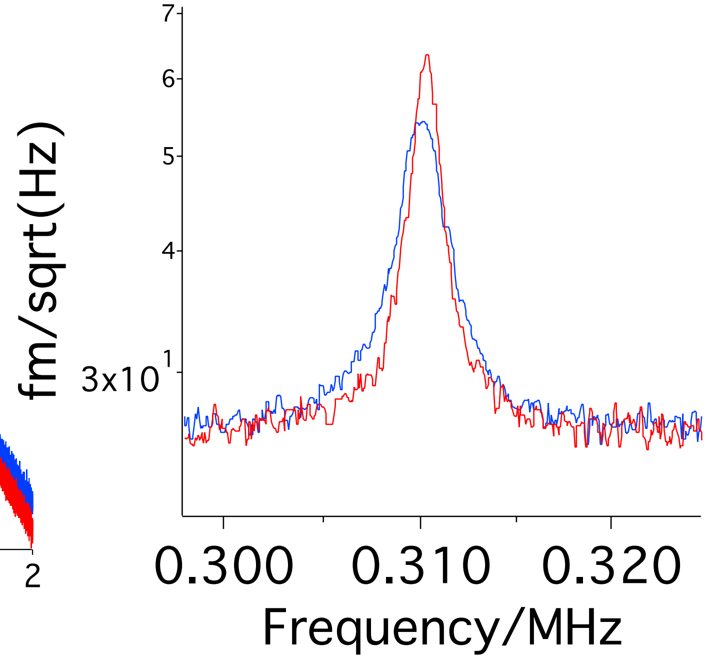
Encased Cantilever Performance





Single clean resonance peak.

High Q and high frequency, performance as in air (F_n=12 fN/√Hz)

-Only small frequency shift (1%) → No Added Mass

-Viscous damping of tip (few μm) and double sided squeeze film damping

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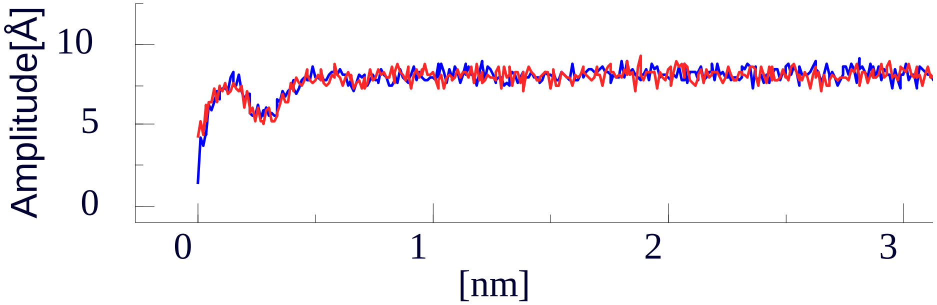
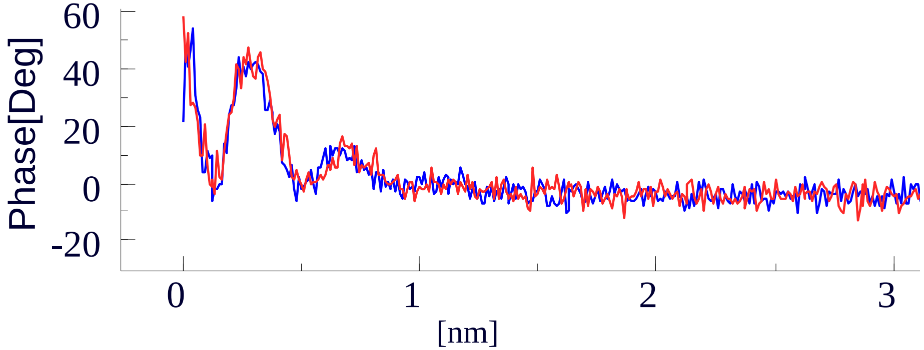
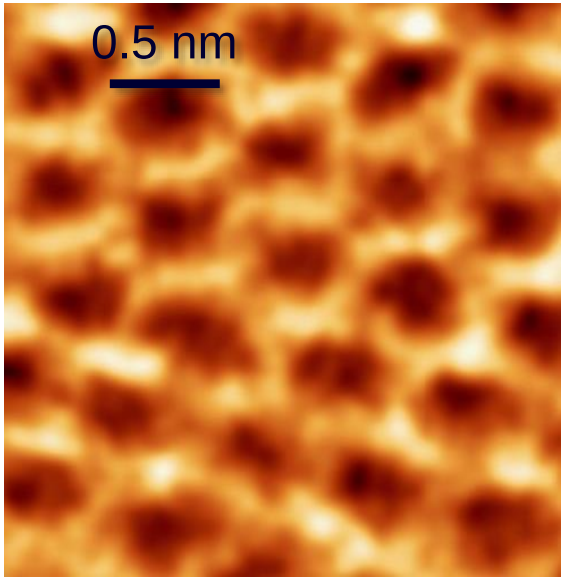
Water at Mica

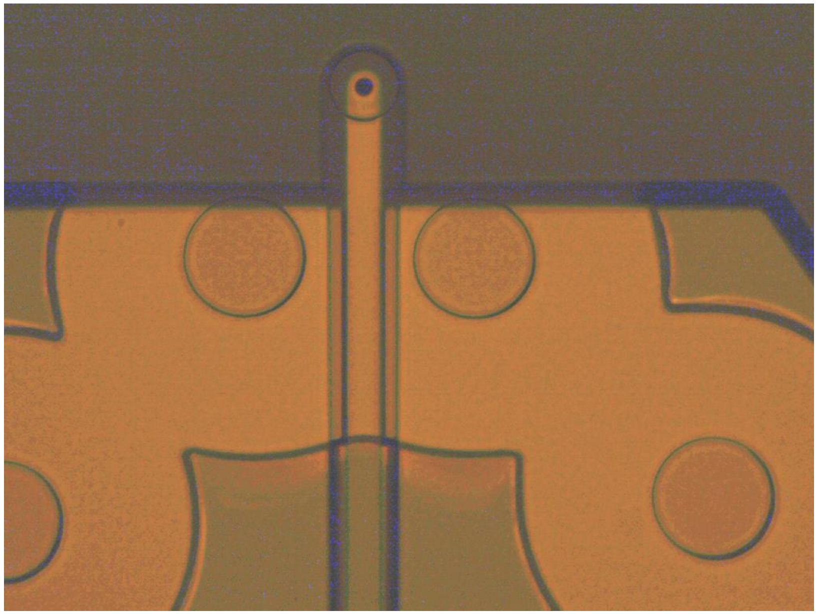


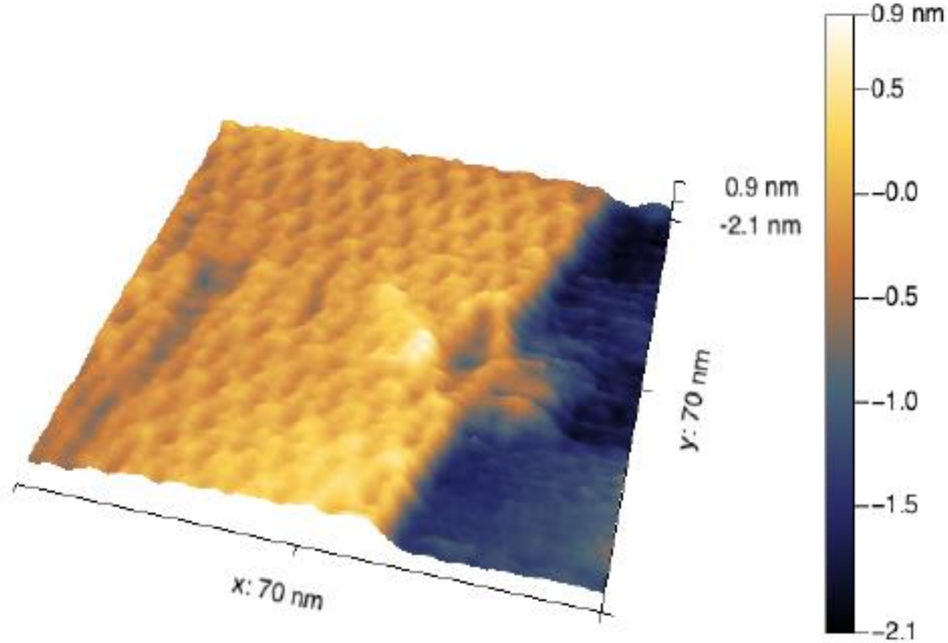




Ultra-small amplitude
displacement of the last few water layers
single curve no averaging

Present Day Encased Cantilevers





SCUBA PROBE TECHNOLOGIES

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Encased Cantilevers
for In-situ AFM

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Hilary Brunner (SPT)
Remo Blum (SPT)

NSF

SCUBA PROBE TECHNOLOGIES

Ziegler, Ashby, et. al., IEEE MEMS, p128, 2014 DOI:10.1109/MEMSYS.2014.6765590.

Desbiolles et. al., Beilstein J. Nanotechnol., 9, 1381-1389, (2018) doi:10.3762/bjnano.9.130.

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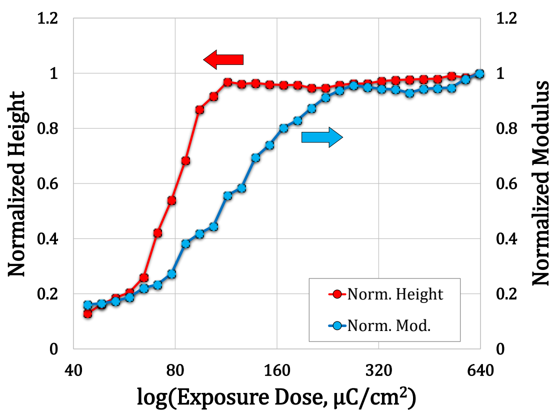
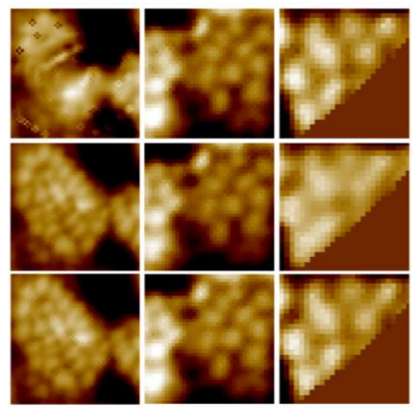
Conclusion

EUV resist design and characterization



High speed Spiral Scan AFM



Encased Cantilevers for In-situ AFM

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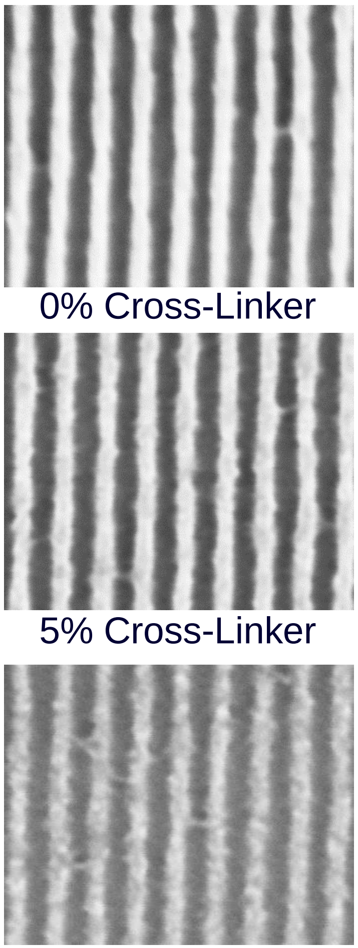
High-Amounts of Cross-linker Due to Chain Progating Reaction

48 nm

LER 3 nm



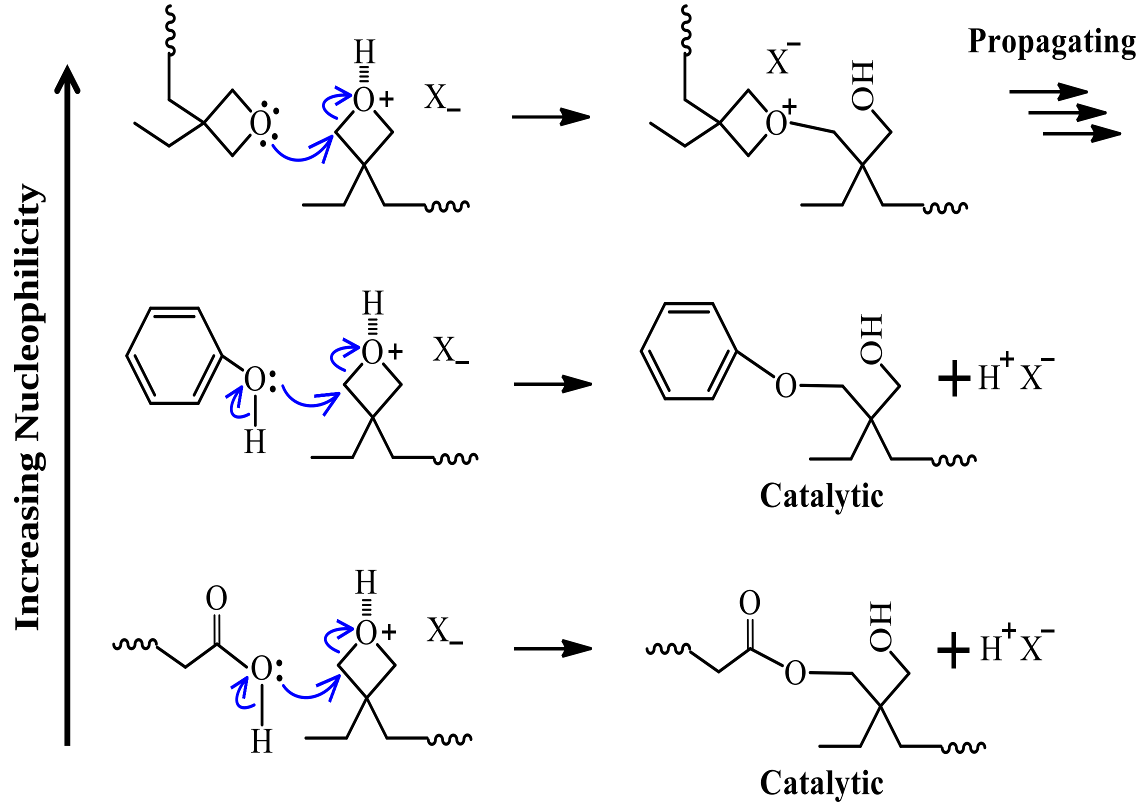
0% Cross-Linker

LER 4 nm

5% Cross-Linker

LER 6 nm

20% Cross-Linker



Nanotechnology 25 315301 (2014) doi:10.1088/0957-4484/25/31/315301

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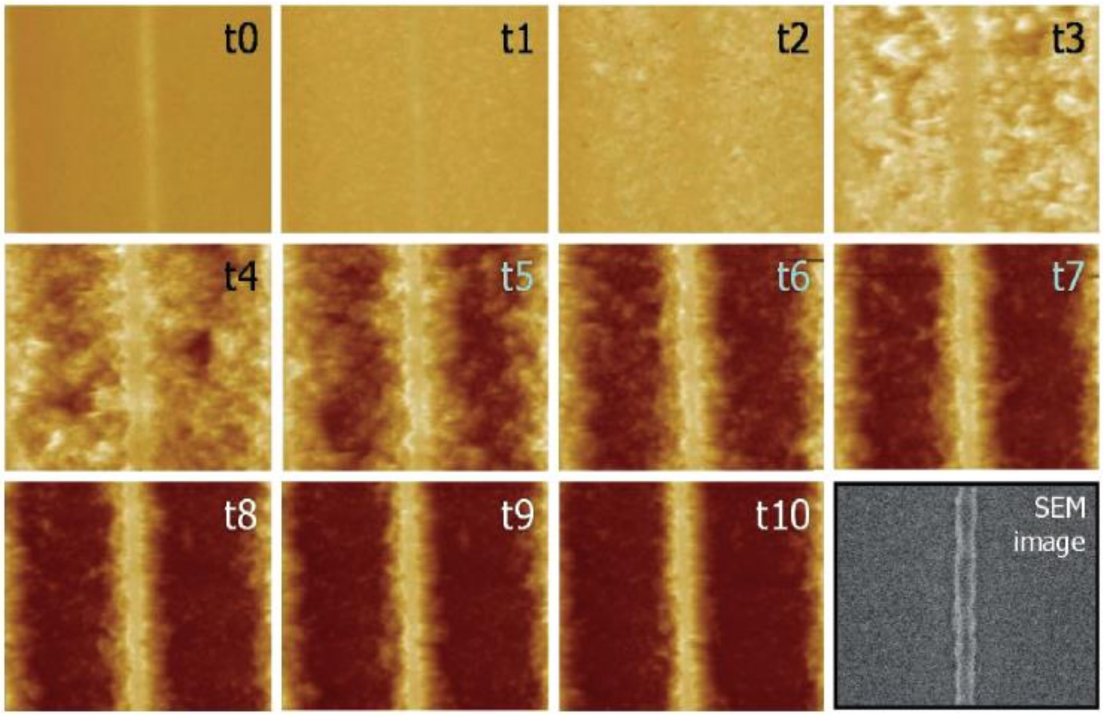
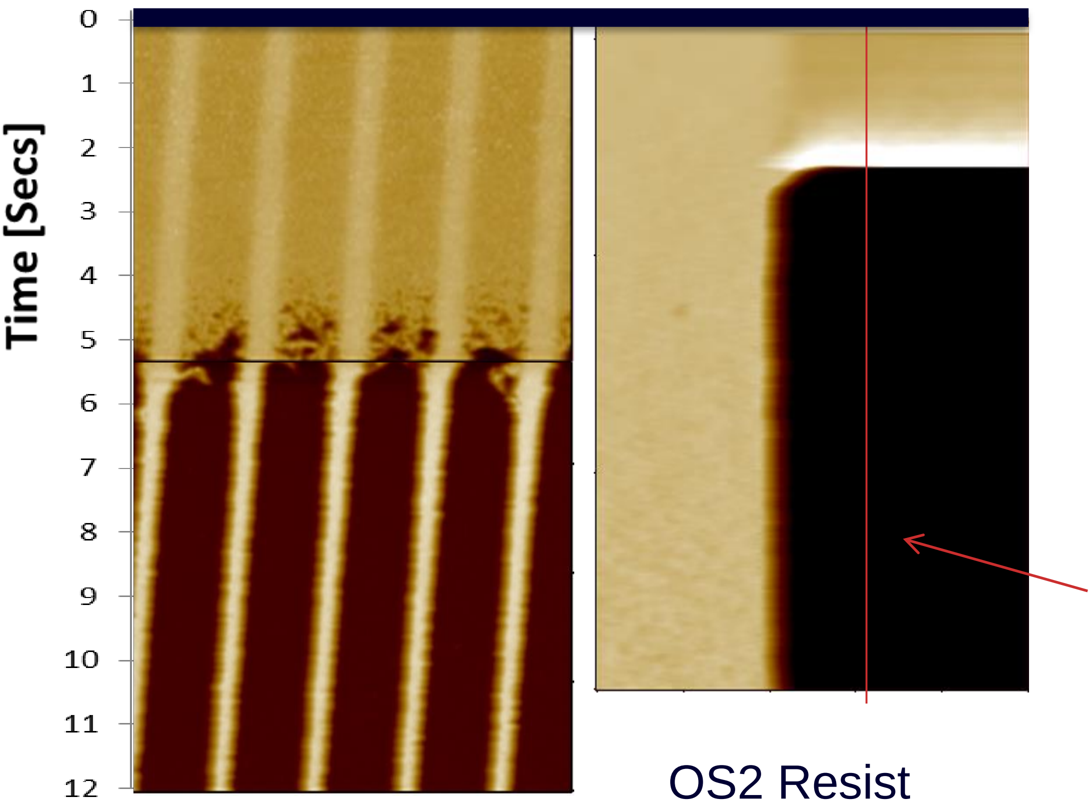
Resist dissolution



Toshiro Itani and Julius Joseph Santillan,
Applied Physics Express, 3, 061601 (2010)

Sematech efforts at the Foundry

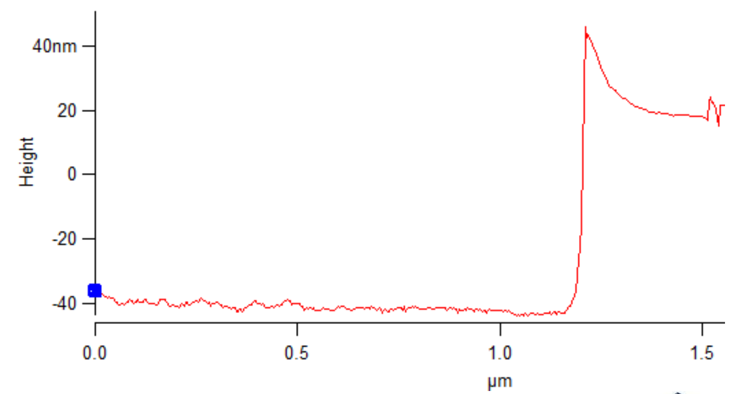
Start of developer injection



JSR1099

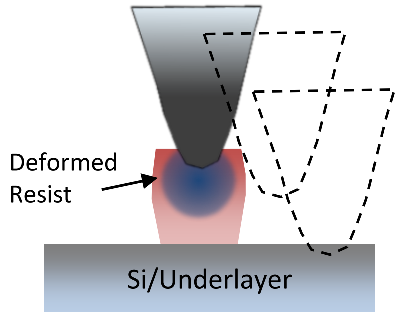
OS2 Resist

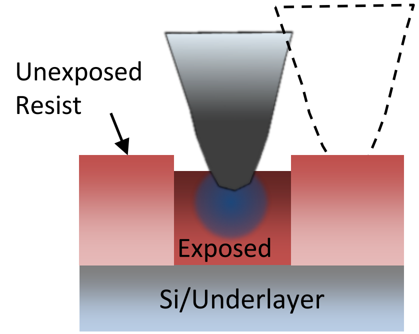
Asylum Research Cypher
(40 lines/s)

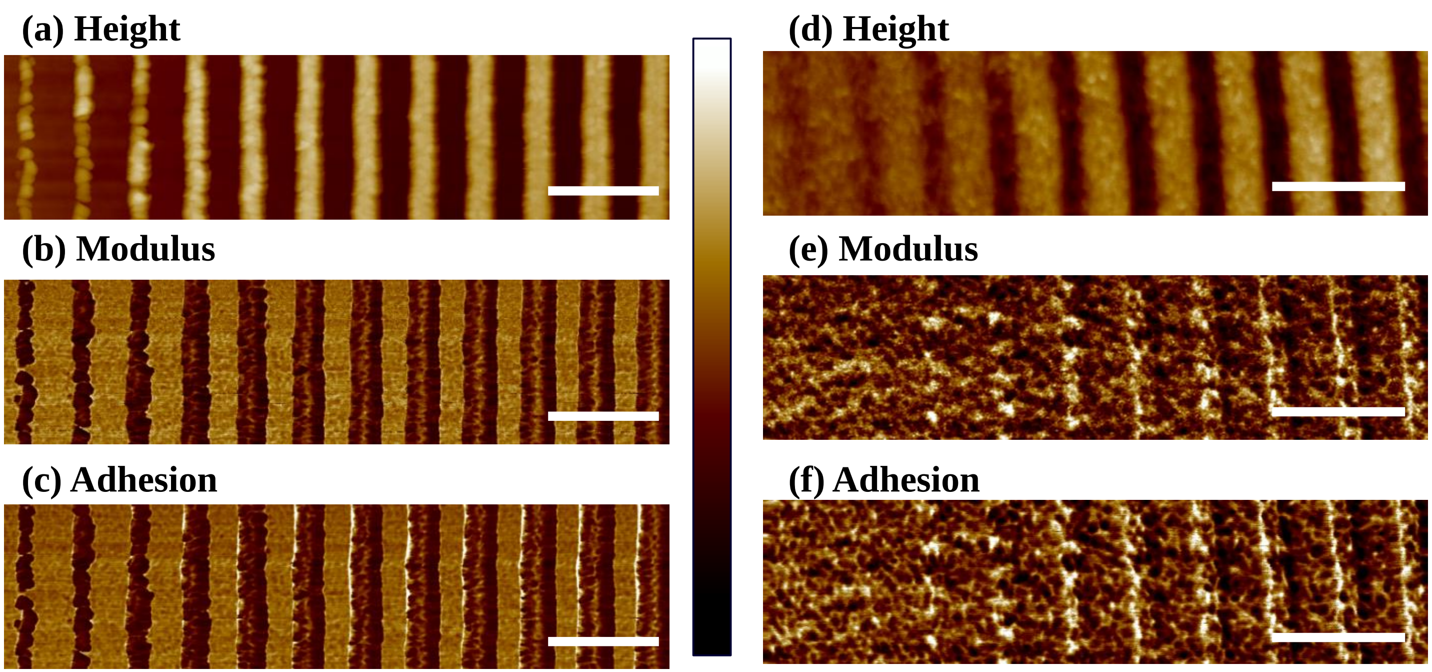


MOLECULAR FOUNDRY

Latent image gives higher resolution





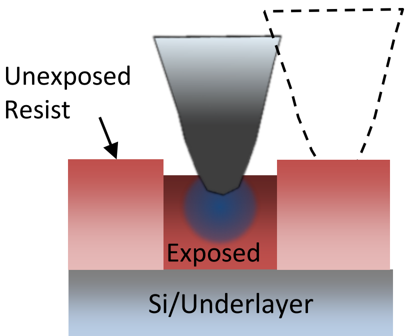


Developed sample

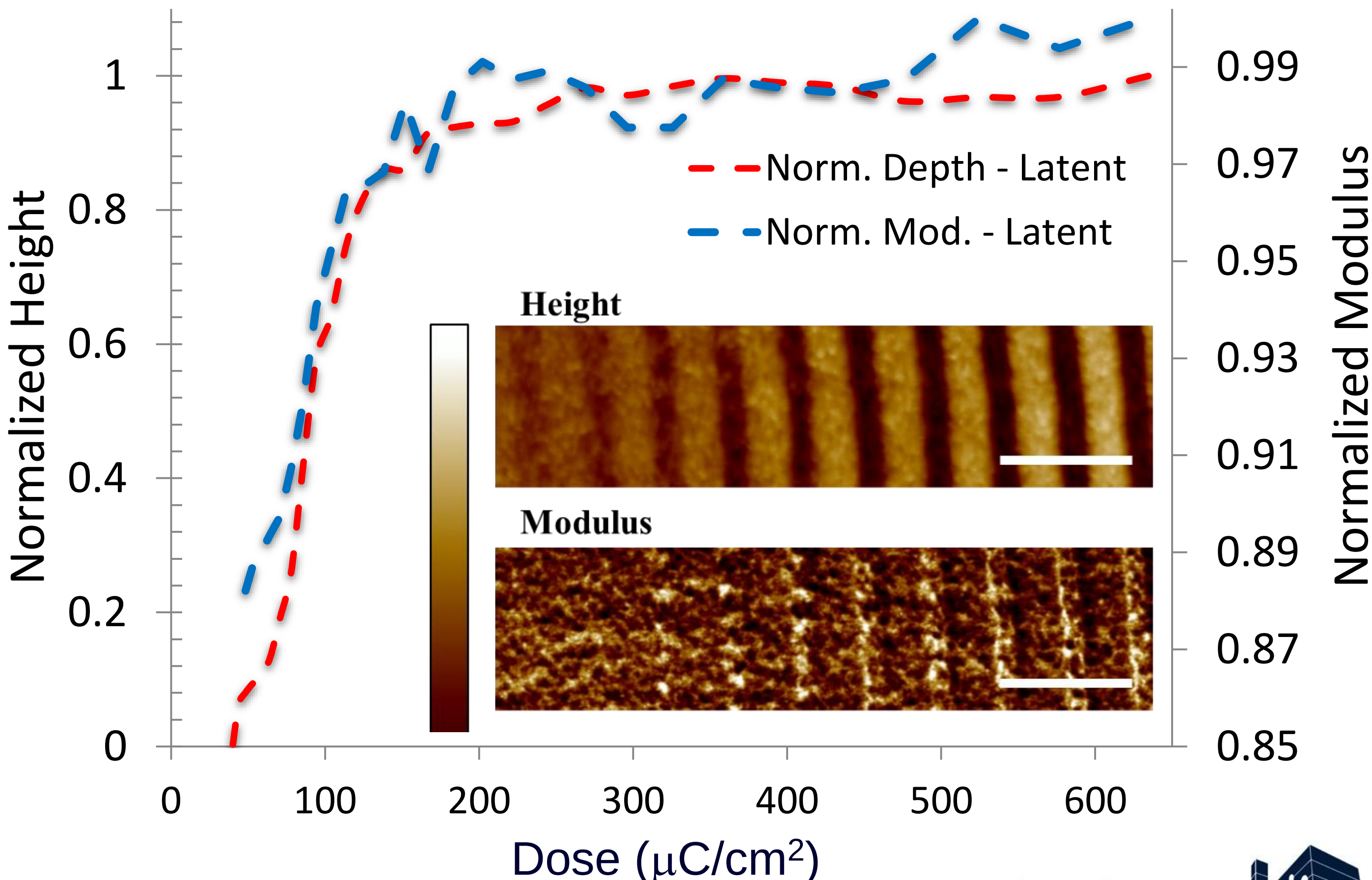
Latent image sample

MOLECULAR FOUNDRY

Latent image depth changes matches modulus



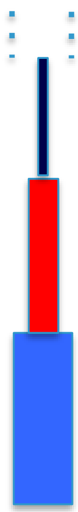
0% Cross-Linker



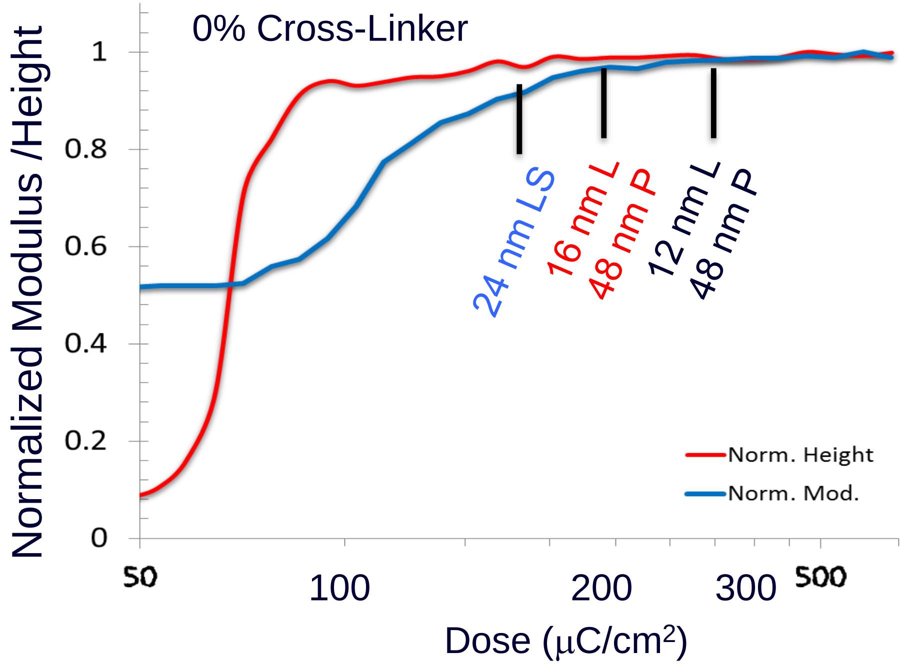
MOLECULAR FOUNDRY

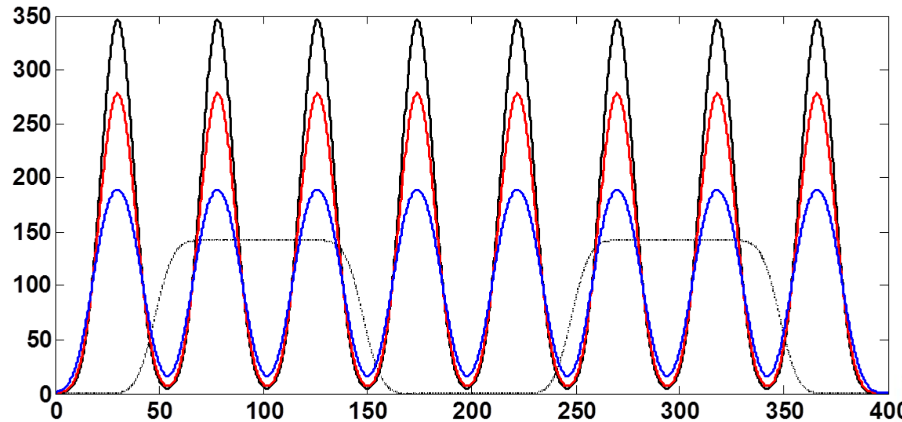
Use biasing to improve modulus

desired linewidth



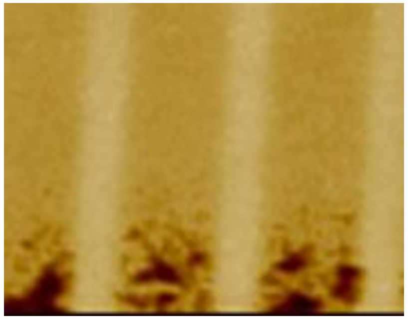
vary drawn linewidth and dose



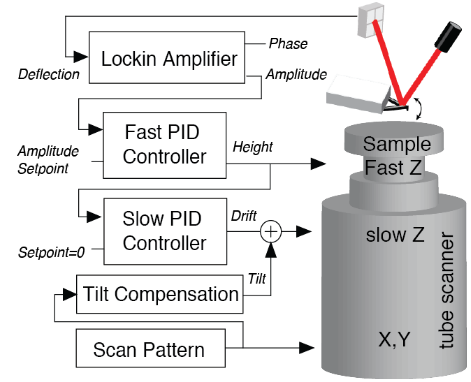


MOLECULAR FOUNDRY

Conclusions

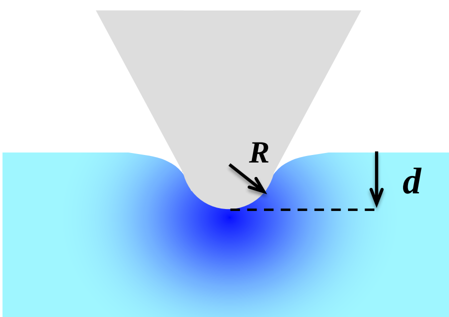


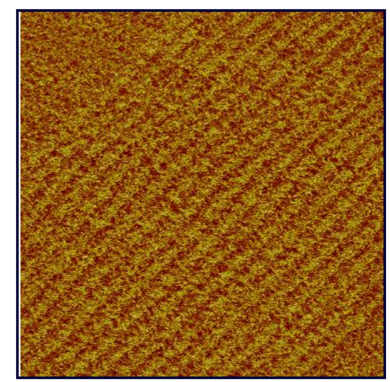
AFM provides high spatial resolution information of dissolution process



15 frames per second of soft material available with new Z piezo design

Modulus Measurement is a promising high resolution probe of chemistry through dose





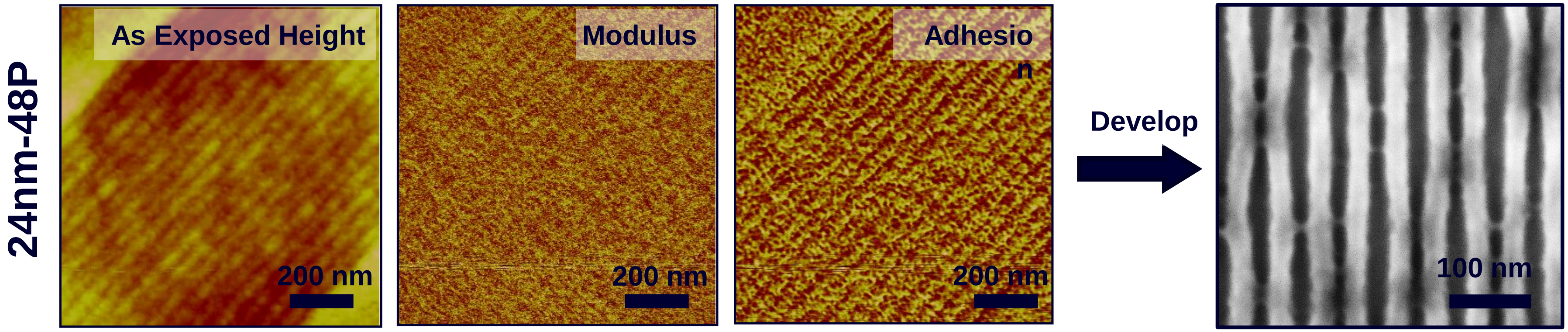
Modulus and Latent Image Depth Show Chemistry Far Beyond Full Thickness

Bias Can be Used to Increase Modulus and Reduce Pattern Collapse

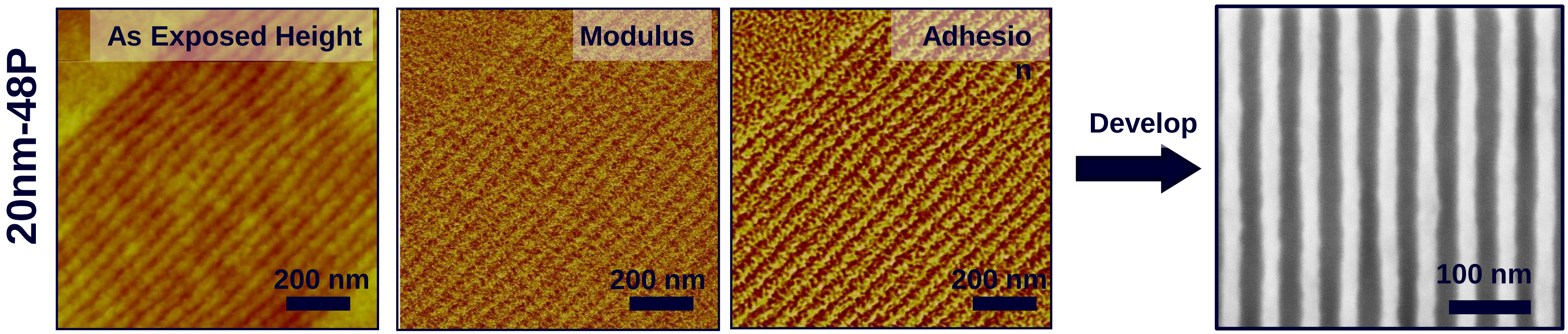
MOLECULAR FOUNDRY

Improved modulus with bias

No Bias:



Bias:



MOLECULAR FOUNDRY

High Speed Spiral Scanning

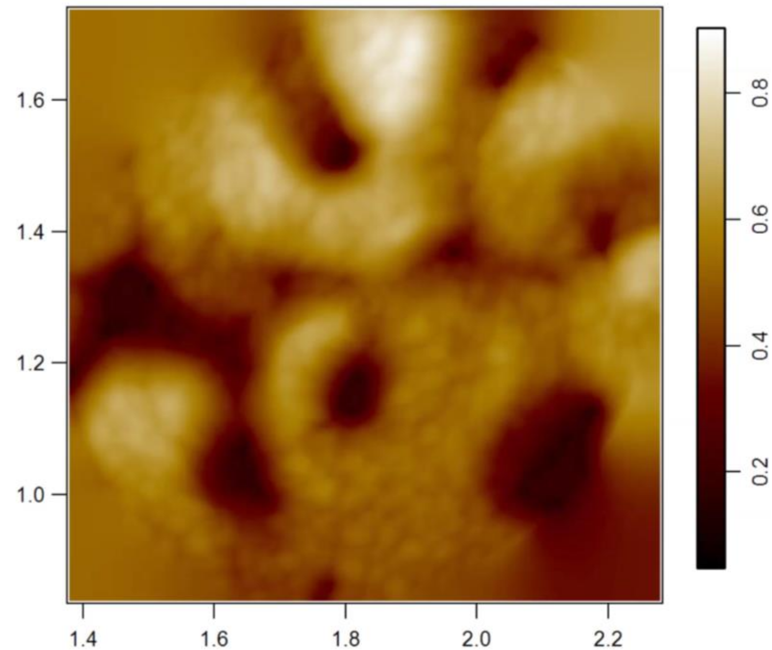
Calcite Dissolution

Asylum MFP3D
90 μm scanner
Usually 100-200s per image

5 μm image
100 loops
5s/image

Fast Survey

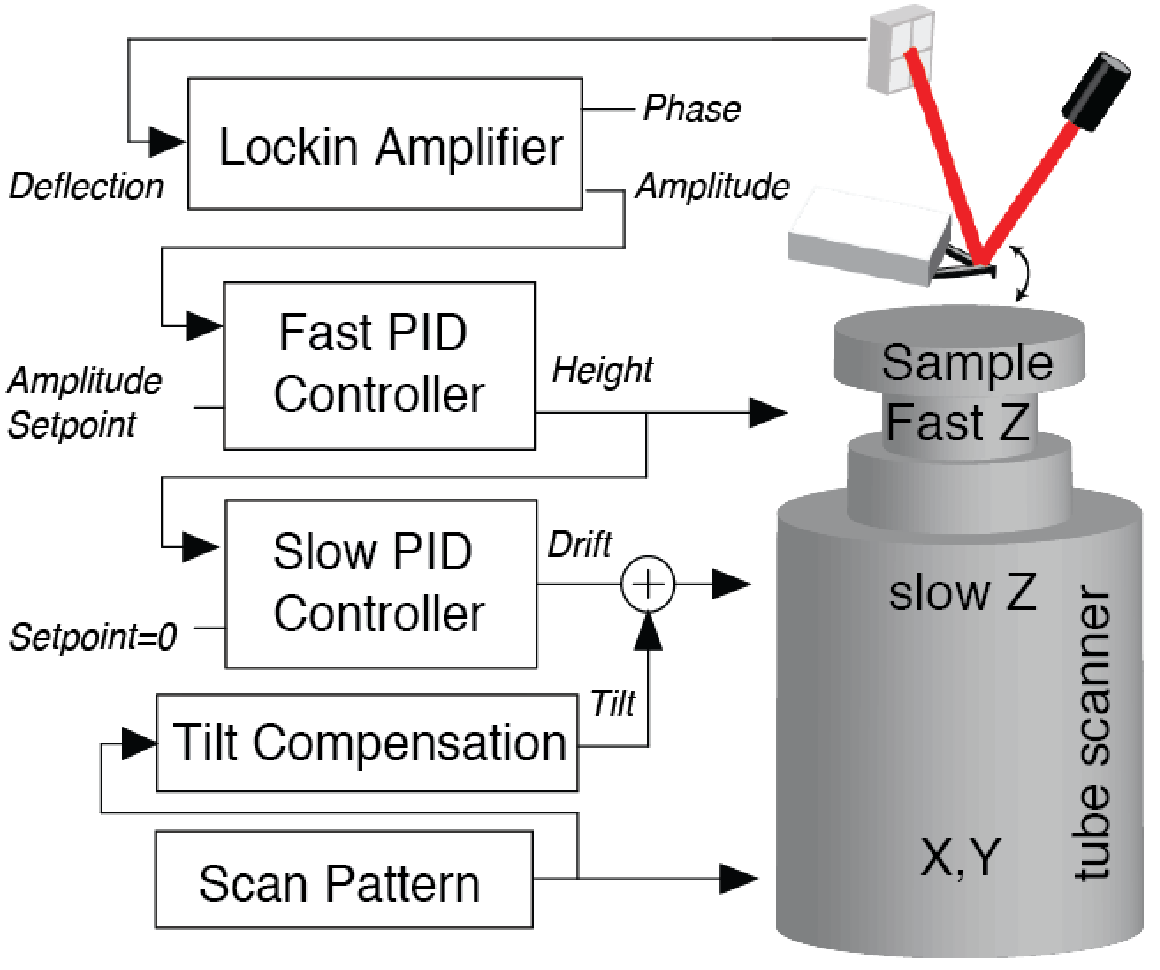
Asylum Cypher
40 μm scanner
Usually 40s per image



1 μm image
85 loops
8 frames/s

MOLECULAR FOUNDRY

Fast Z with tilt correction



Slow Z piezo handles drift and sample tilt.

Fast Z only does topography.