Advances in X-ray Reflection Grating Technology

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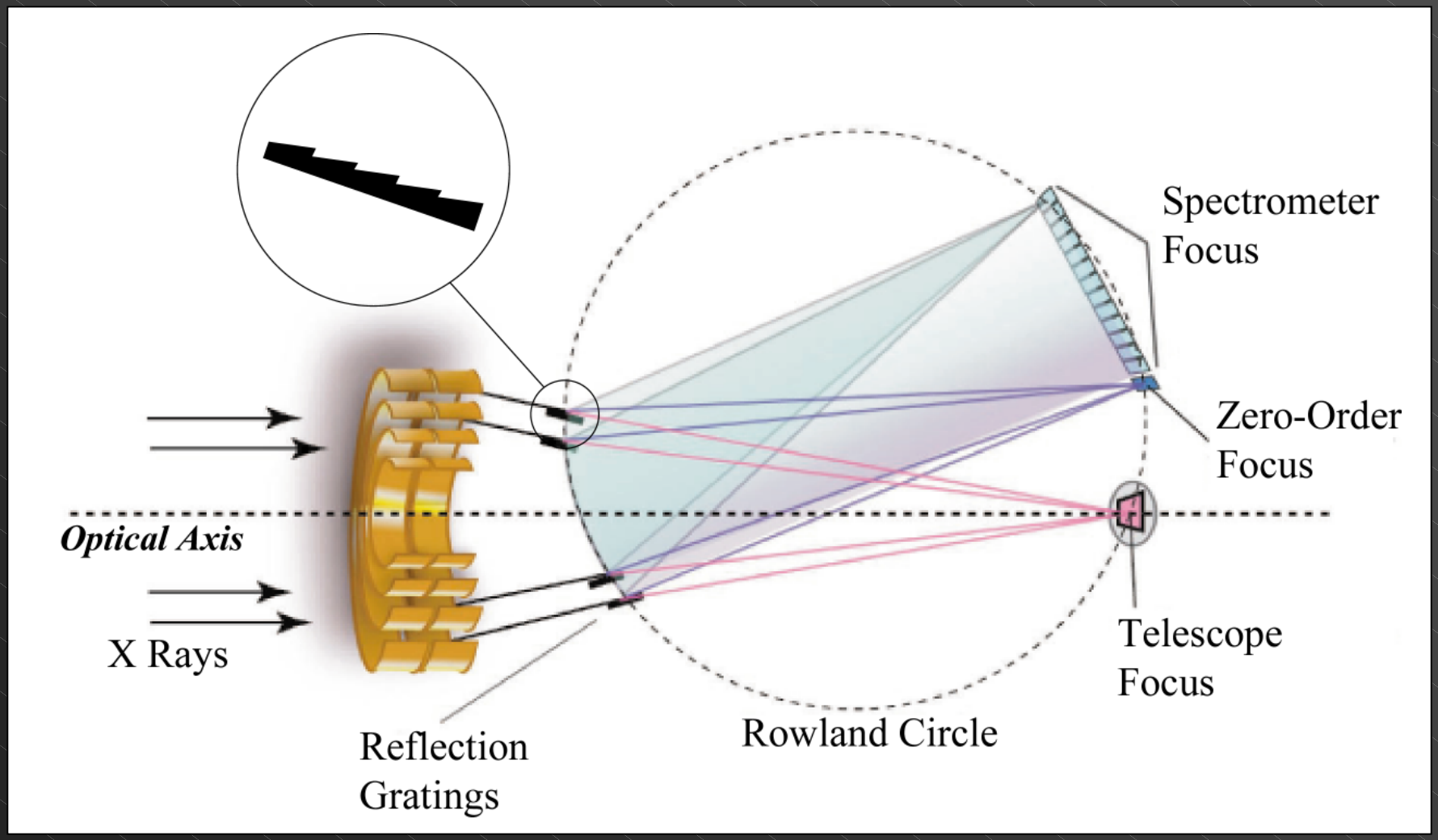
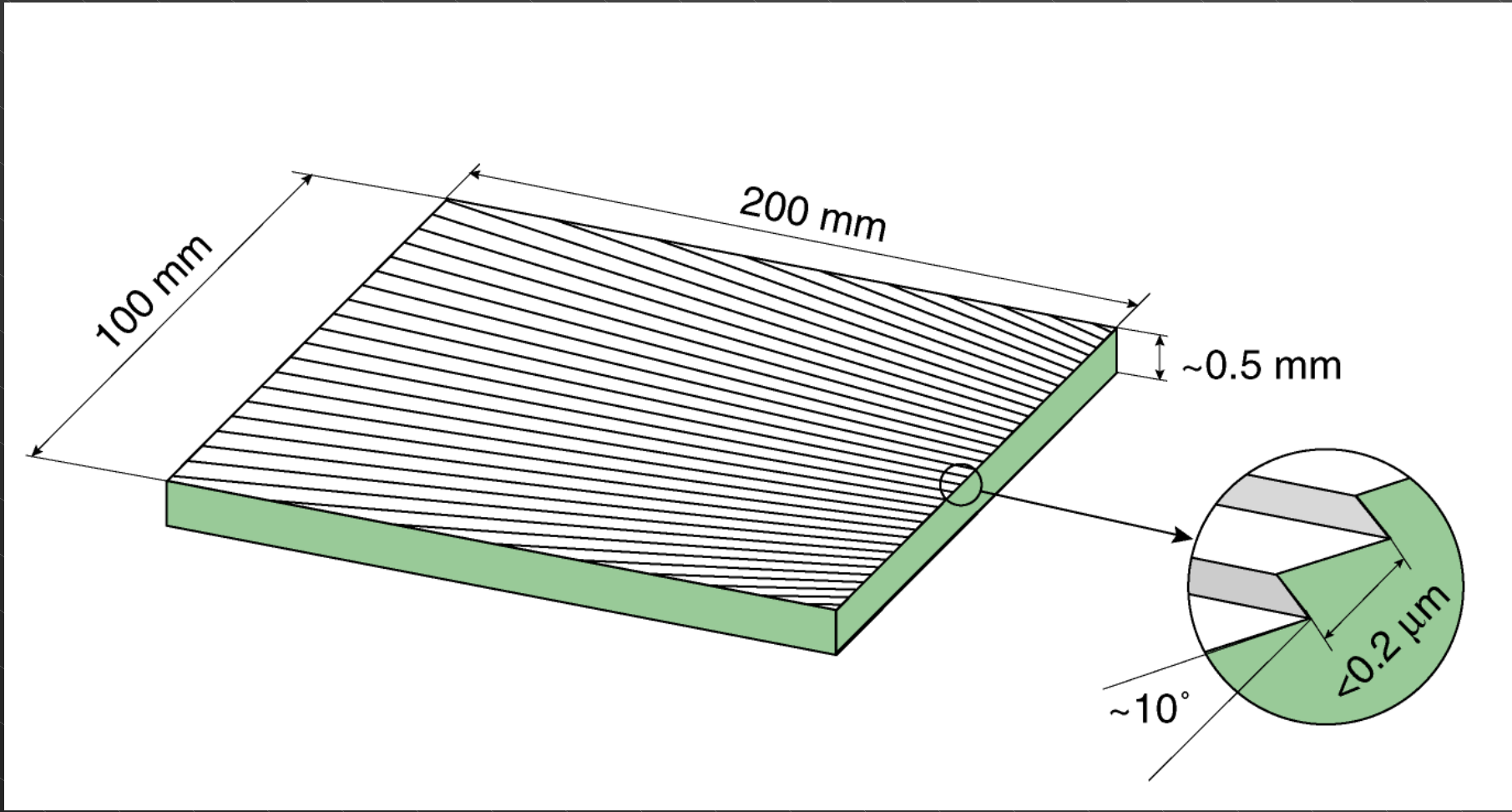
Reflection Grating Spectrometer



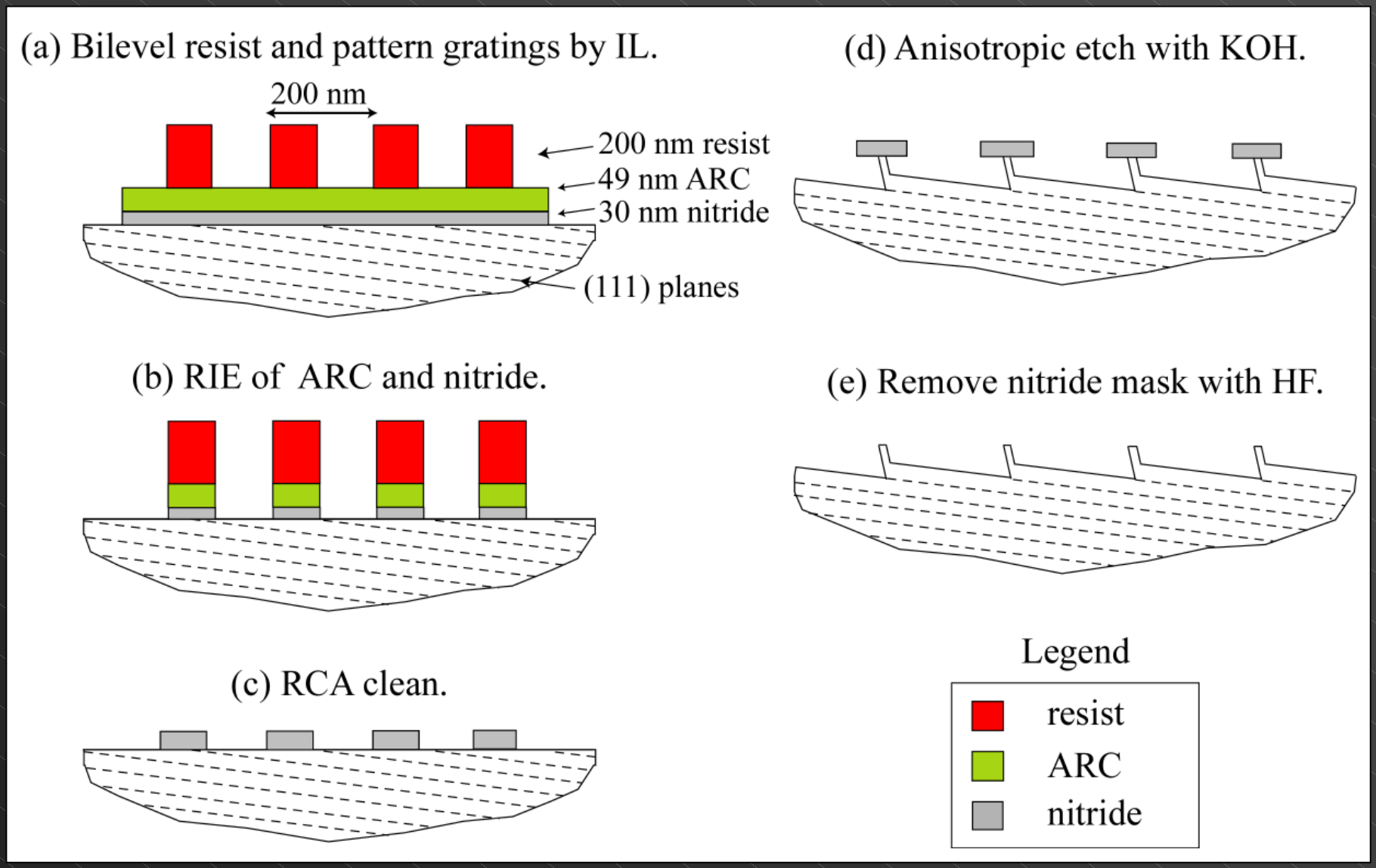
(J. Grady, Goddard Space Flight Center)

Reflection Grating Spectrometer

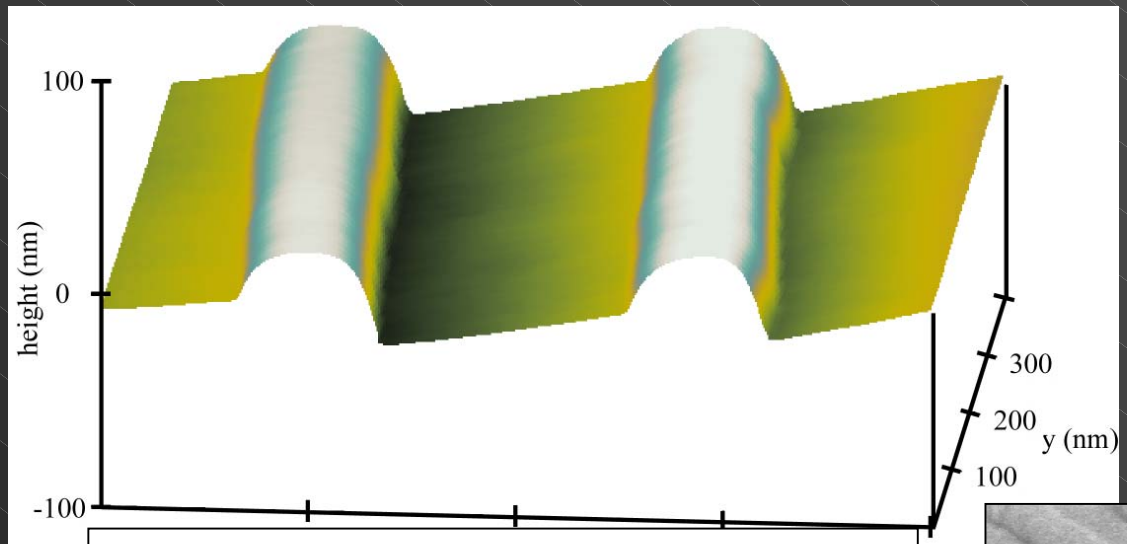


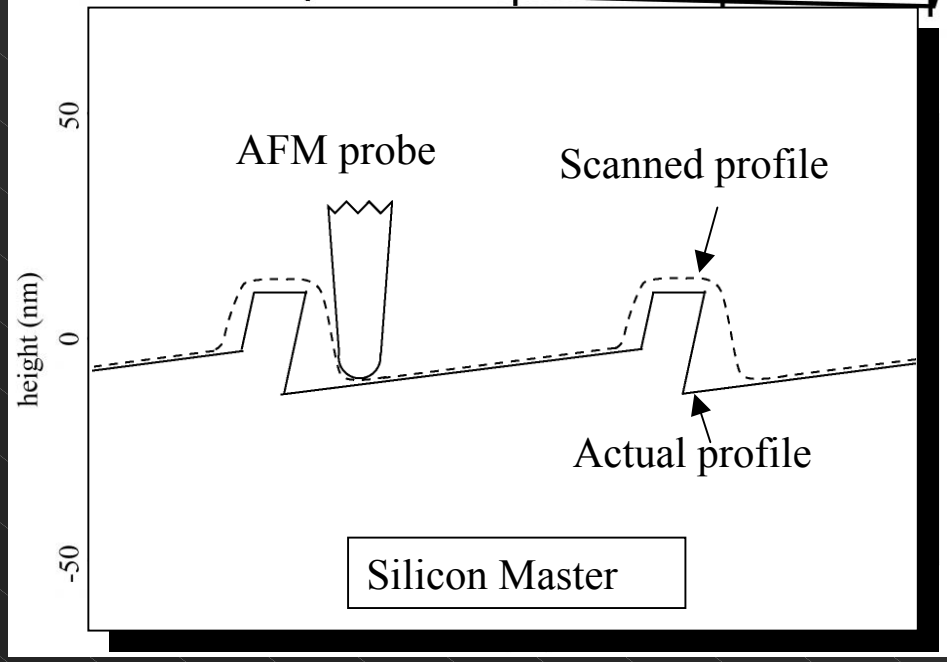
- Flatness < 1.0 µm over 200 mm
- Roughness < 0.5 nm

Process for Silicon Blazed Grating



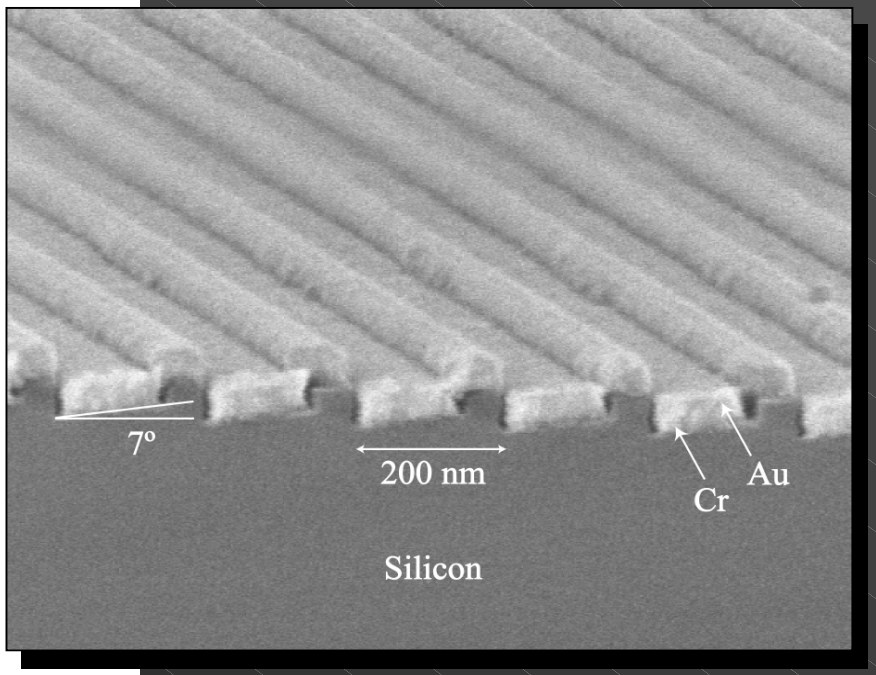
200 nm Si Master with 7º Blaze





- Roughness < 0.2 nm
- Rounding = AFM artifact
- Radius of probe ~ 10 nm

Coated with Cr and Au



Atomic Force Micrograph (AFM)

Scanning Electron Micrograph (SEM)

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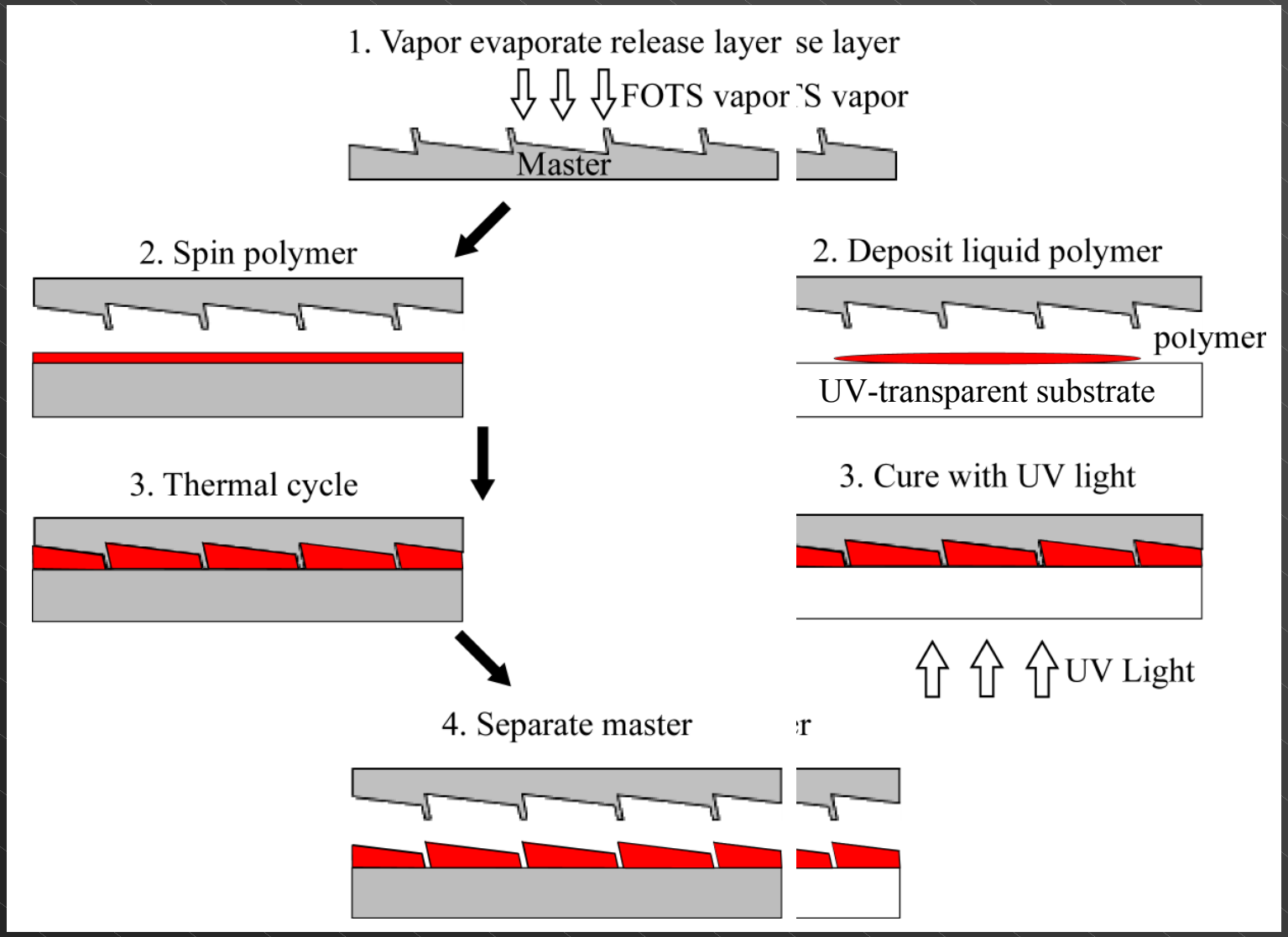
Replication: Nanoimprint Lithograpy

Thermal-cure UV-cure



FOTS (Tridecafluoro-1,2,2,2-Tetrahydrooctyltrichlorosilane)

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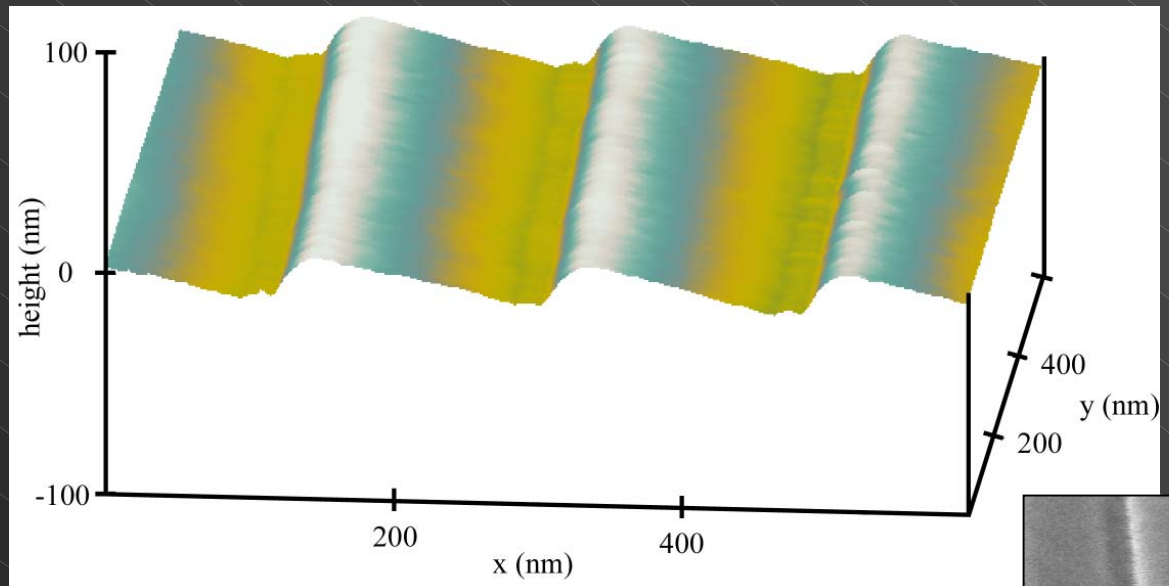
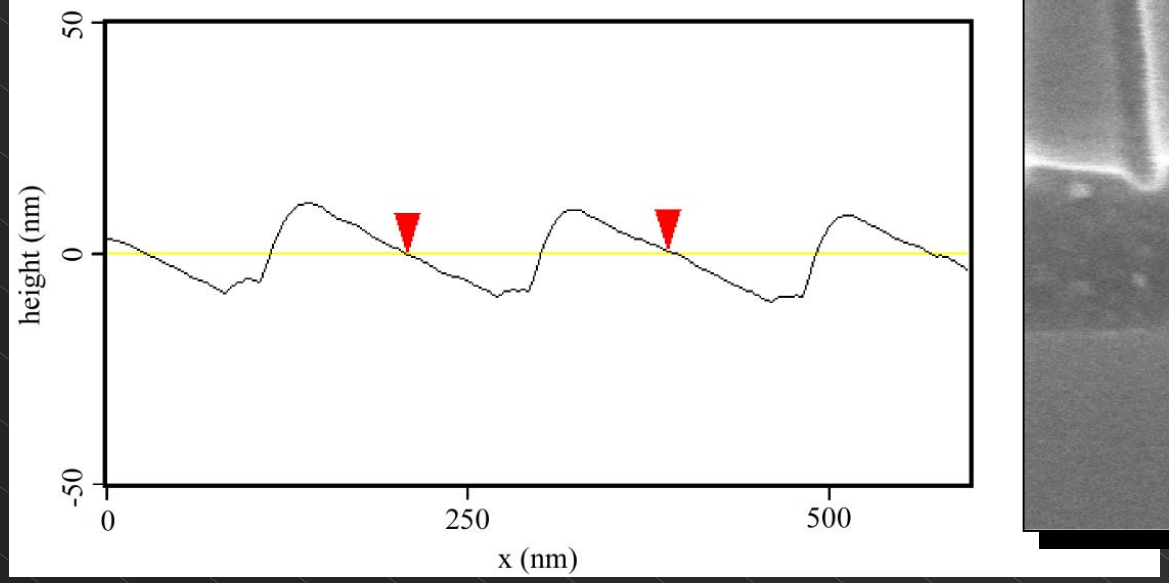
Thermal-imprint 7º Blazed Grating

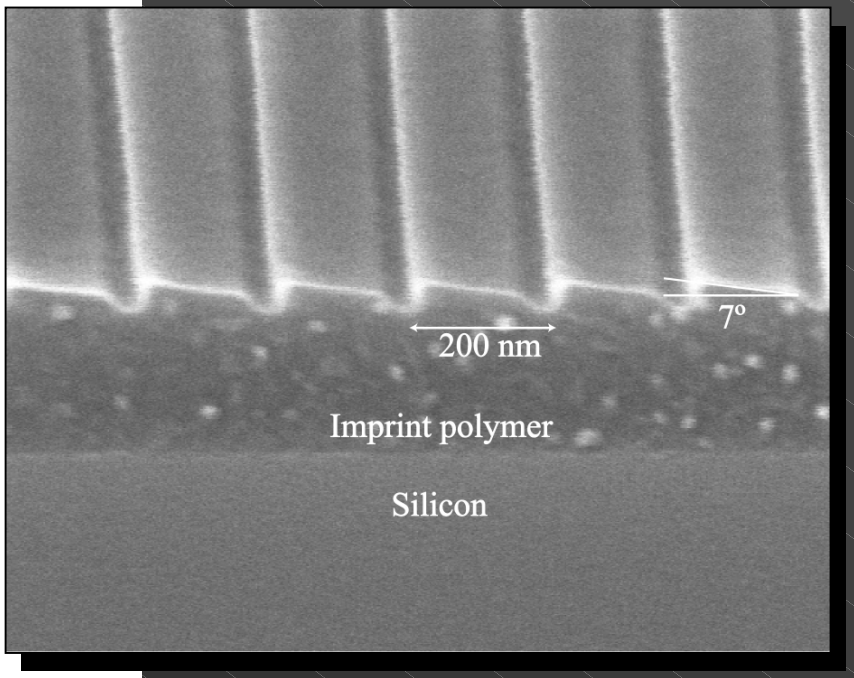




AFM

- Imprinted area = 100 mm wafer
- Roughness < 0.2 nm
- Rounding = AFM artifact
- Trenches present

SEM



(Gratings imprinted at Nanonex, Corp.)

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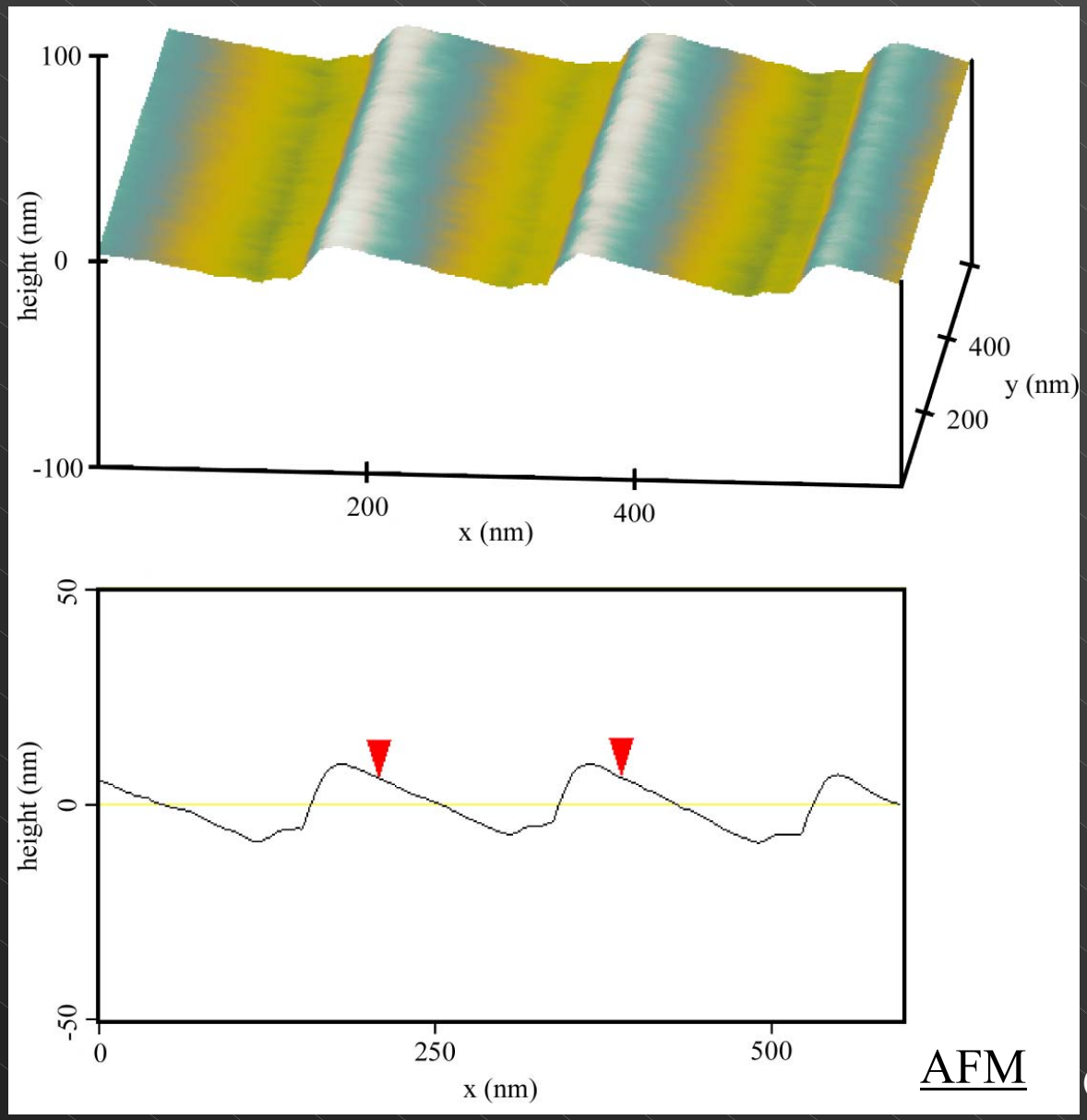
UV-imprint 7º Blazed Grating



- Imprinted area = 100 mm wafer
- Roughness < 0.2 nm
- Rounding = AFM artifact

(Gratings imprinted at Nanonex, Corp.)

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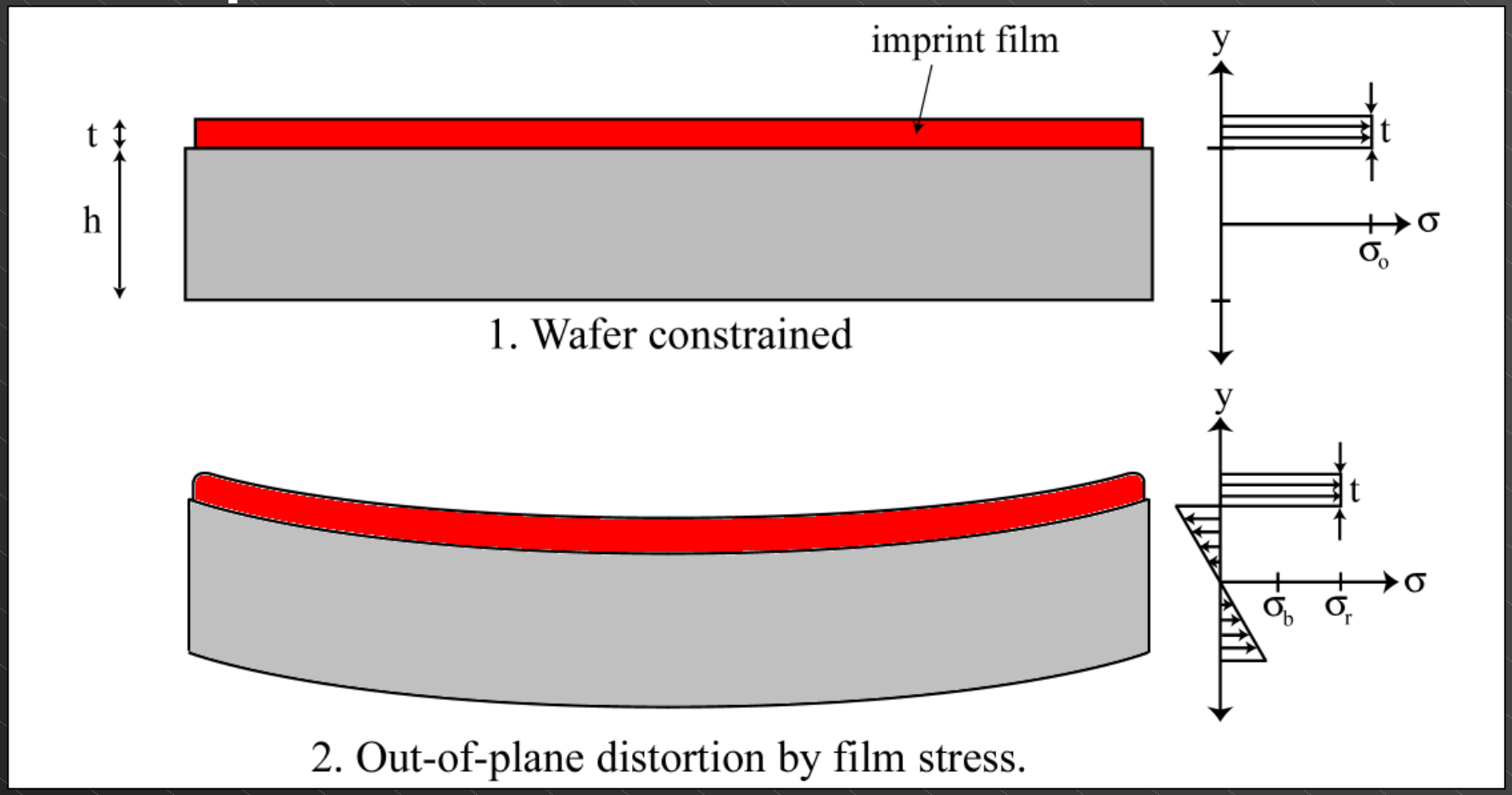
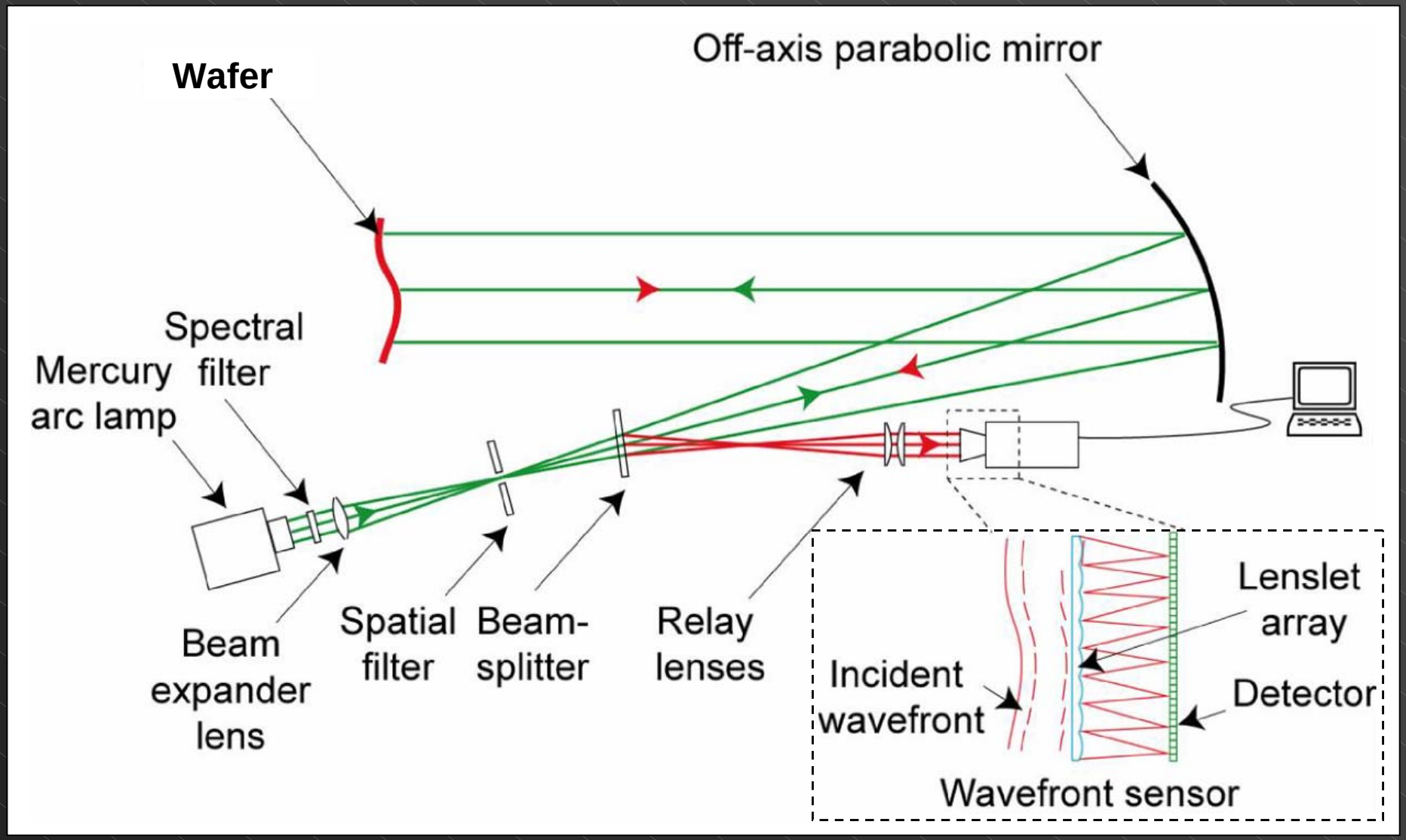
Replication Induced Distortion



- Stoney's equation for thin film: $\frac{1}{R} = \frac{6\sigma_o t}{E_{bi} h^2}$
- Optic flatness < 500 nm over 100 mm

Shack-Hartmann Metrology Tool



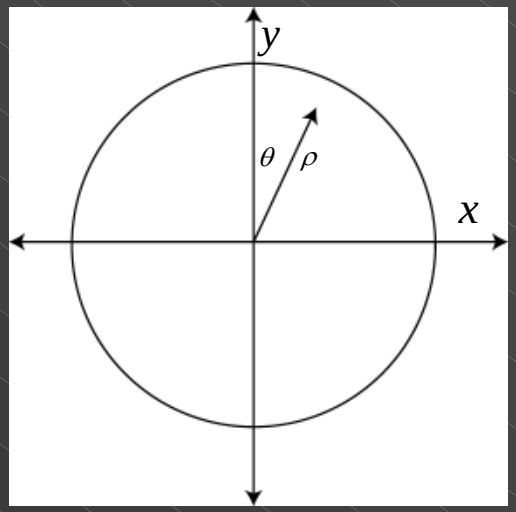
C. R. Forest *et al.*, Opt. Eng., **43** (3), 742 (2004)

Zernike Polynomials

- Any waveform can be represented as linear combinations of Zernike polynomials
- Series of complete, orthogonal polynomials over unit circle
- Defined as,

$$ {}^{e}U_n^l(\rho,\theta) = R_n^l(\rho)\cos l\theta, $$

$$ {}^{o}U_n^l(\rho,\theta) = R_n^l(\rho)\sin l\theta, $$

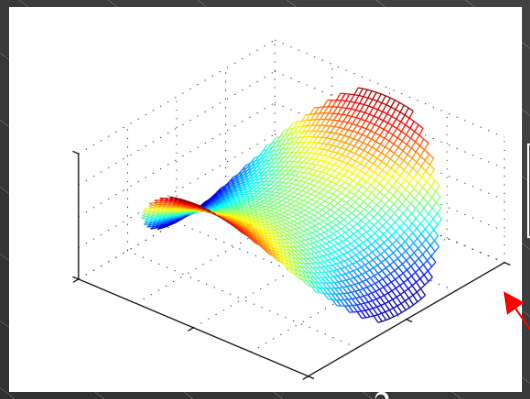


- Where,

$$ R_n^{n-2m}(\rho) = \sum_{s=0}^{m} \frac{(-1)^s (n-s)!}{s!(m-s)!(n-m-s)!} \rho^{n-2s}, $$

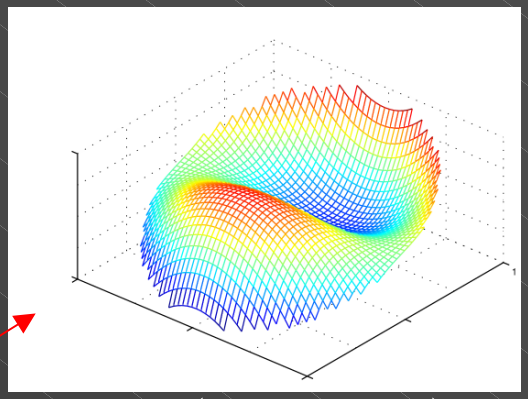
- Used to describe modes of wavefront aberration

Zernike Polynomial Decomposition



$Z_{22} = 0.5$

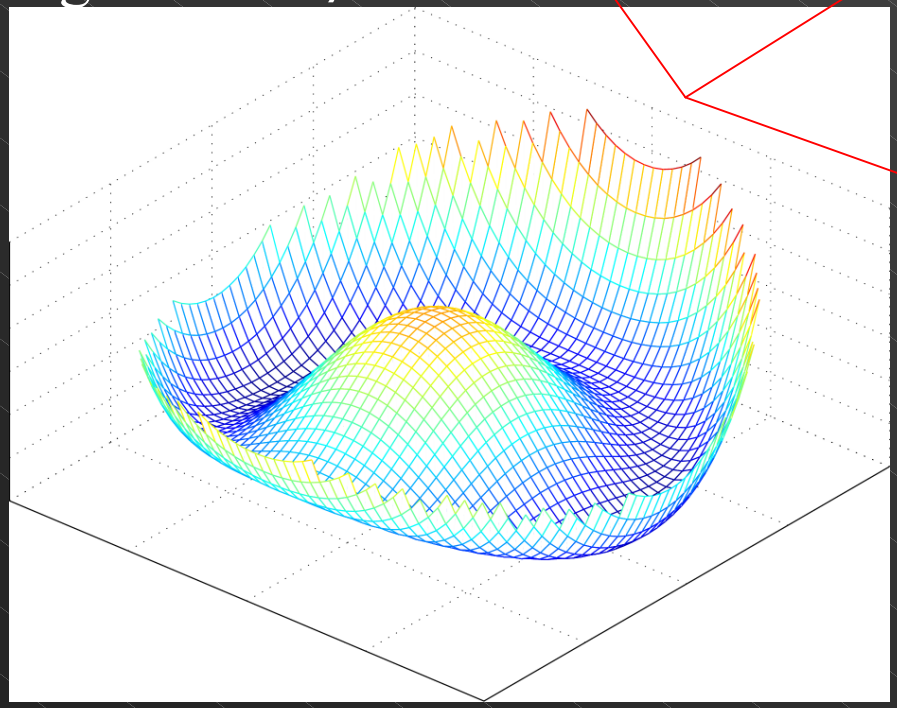
$Z_{32} = 0.5$

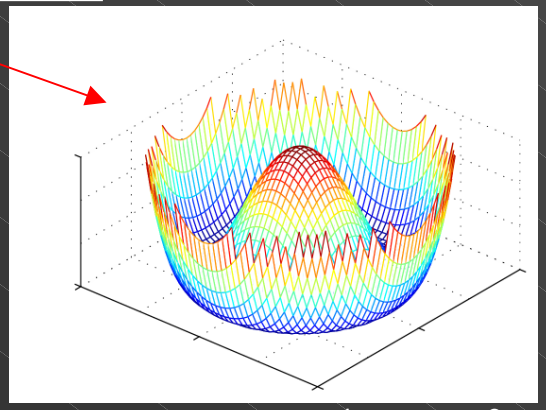


Astigmatism: $\rho^2 \cos 2\theta$

Coma: $\left(3\rho^3 - 2\rho\right)\cos\theta$

$Z_{42} = 1$





Spherical: $6\rho^4 - 6\rho^2 + 1$

Arbitrary wavefront

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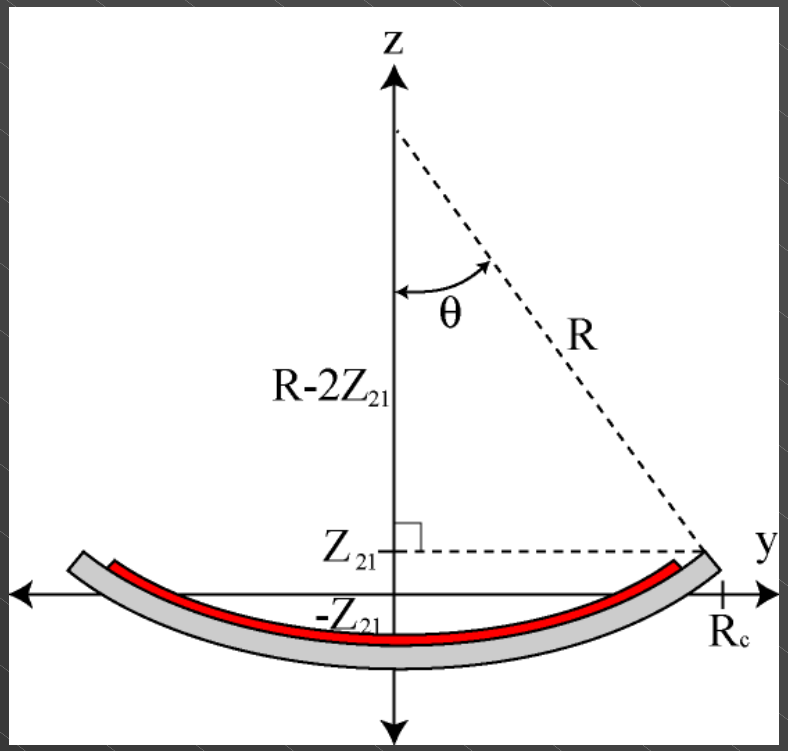
Z_{21} Coefficient

- With Stoney's equation,

$$\sigma_o = \frac{2E_{bi}h^2}{3tR_c^2}\Delta Z_{21} = C\,\Delta Z_{21}$$



- Distortion changes Z_{21} only
- The U_{21} polynomial is,

$$\frac{1}{R} = \frac{4Z_{21}}{R_c^2}$$

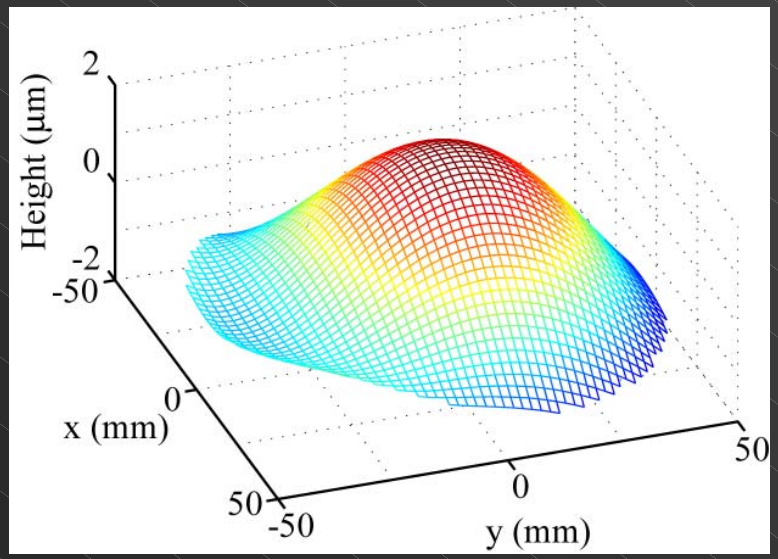
- Radius of curvature for U_{21},

$$U_{21}(\rho) = 2\rho^2 - 1,$$

Wafer Before and After Thermal-NIL

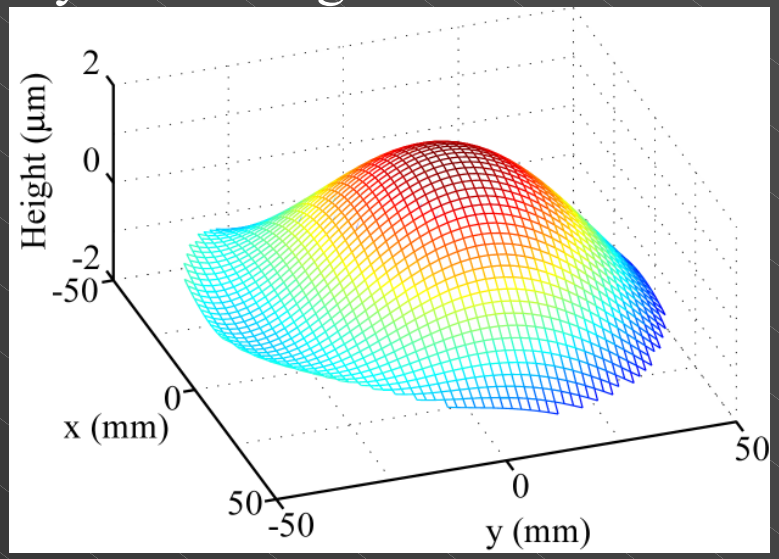
Before

- Silicon wafer



After

- Polymer average thickness ~ 85 nm



Zernike Coefficients (µm)	Z_{20}	Z_{21}	Z_{22}	Z_{30}	Z_{31}	Z_{32}	Z_{33}
Before	0.120	-1.407	0.023	0.151	-0.261	-0.648	0.057
After	0.032	-1.390	0.069	0.162	-0.234	-0.659	0.078

ΔZ_{21} = 17 nm

repeatability ~ 35 nm

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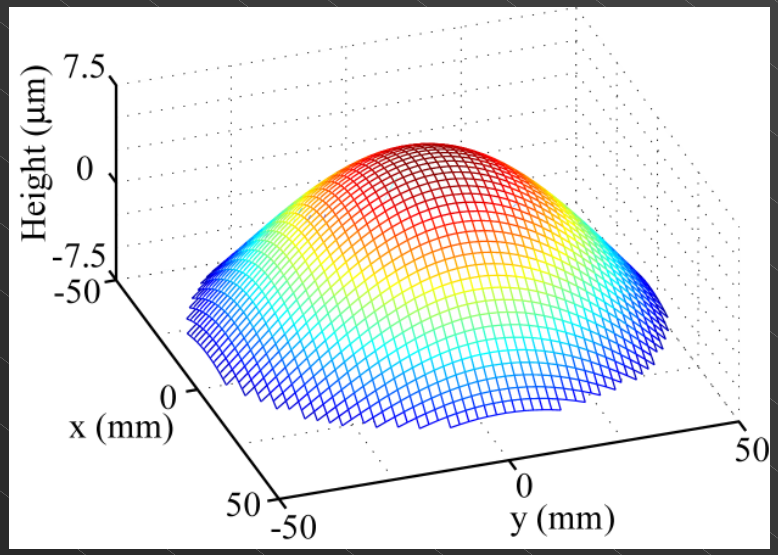
Wafer Before and After UV-NIL

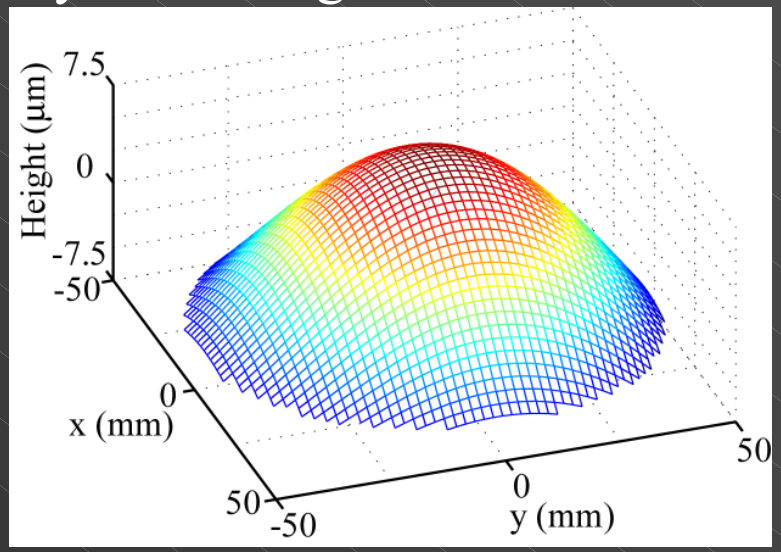
Before

- Fused silica wafer



After

- Polymer average thickness ~ 285 nm



Zernike Coefficients (µm)	Z_{20}	Z_{21}	Z_{22}	Z_{30}	Z_{31}	Z_{32}	Z_{33}
Before	-0.031	-6.234	-0.209	0.087	-0.486	-0.307	-0.004
After	-0.029	-6.262	-0.163	0.070	-0.355	-0.641	0.002

ΔZ_{21} = -28 nm

repeatability ~ 35 nm

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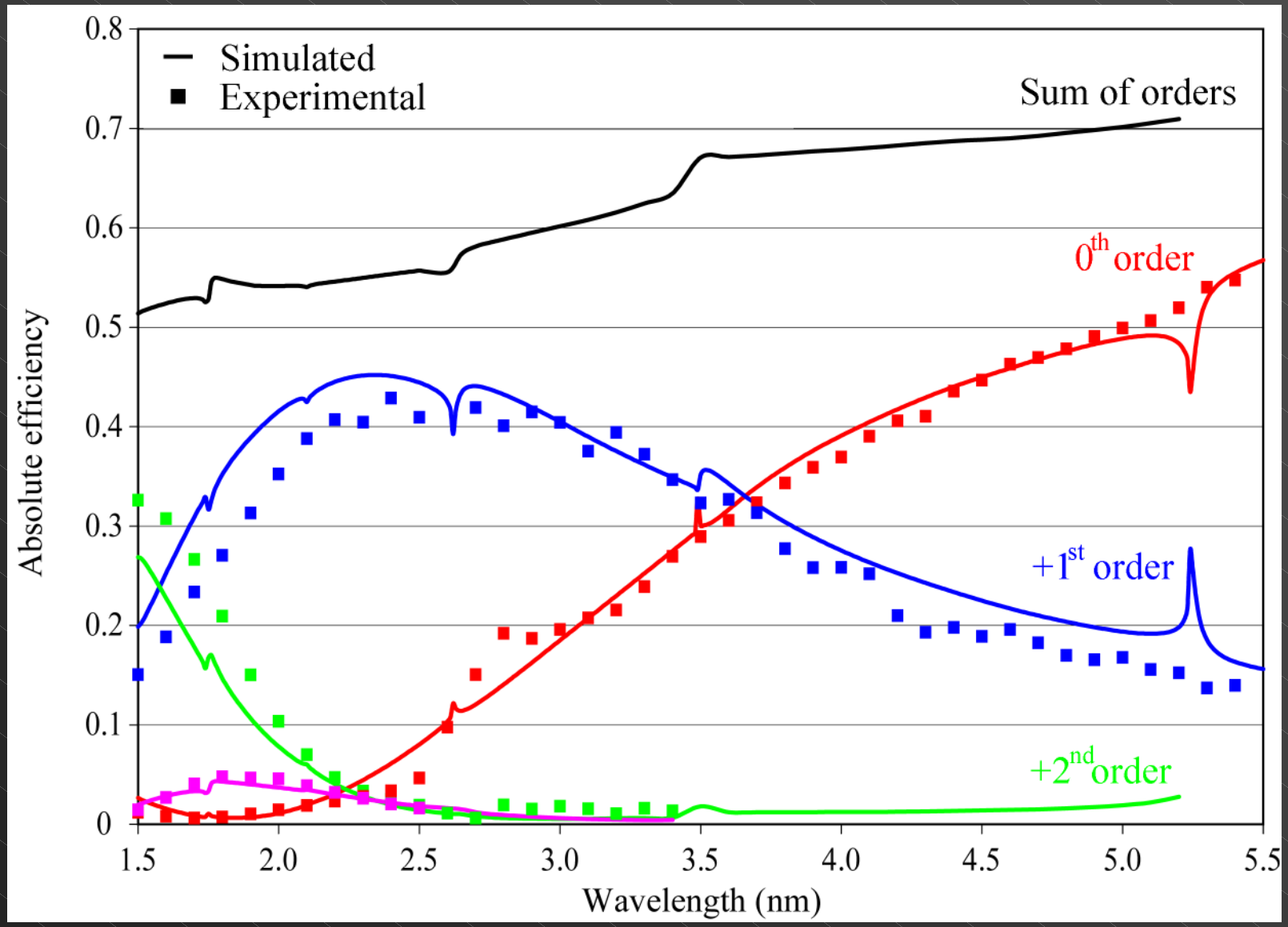
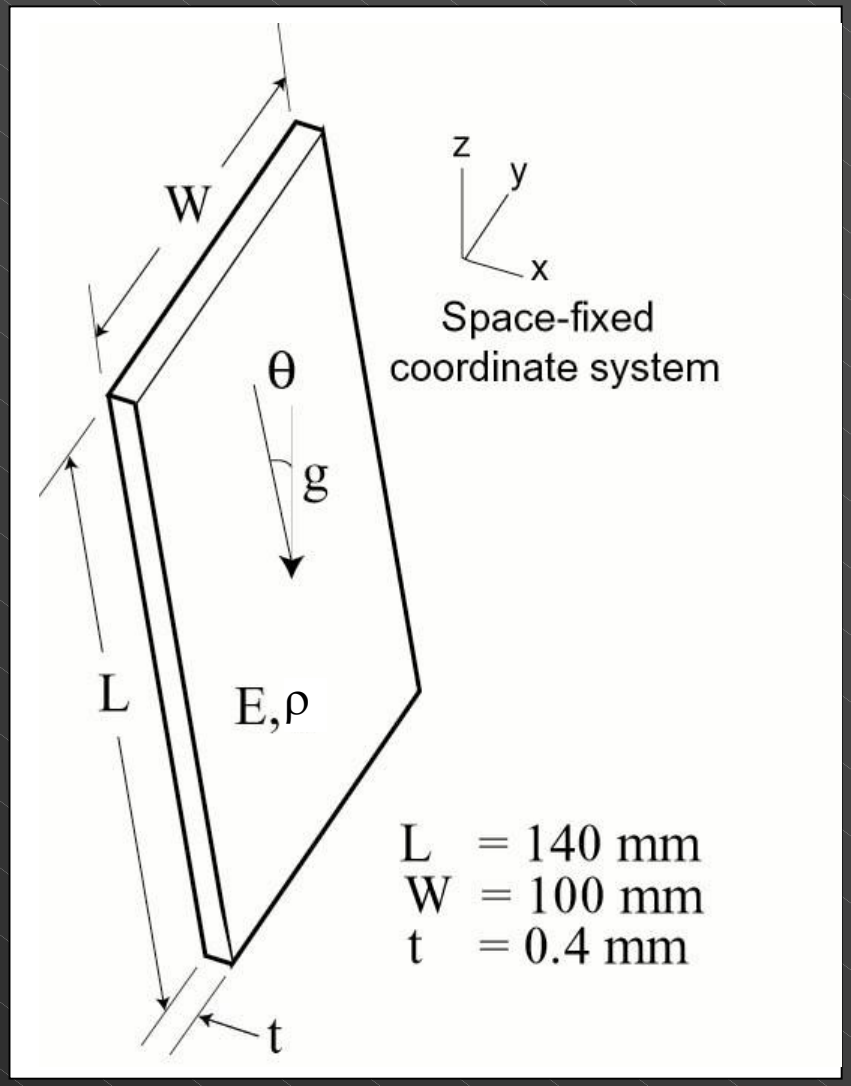
Preliminary X-ray Diffraction Efficiency



(Testing conducted at National Synchrotron Light Source of Brookhaven National Laboratory, simulation by International Intellectual Group, Inc)

Foil Optic Deformation

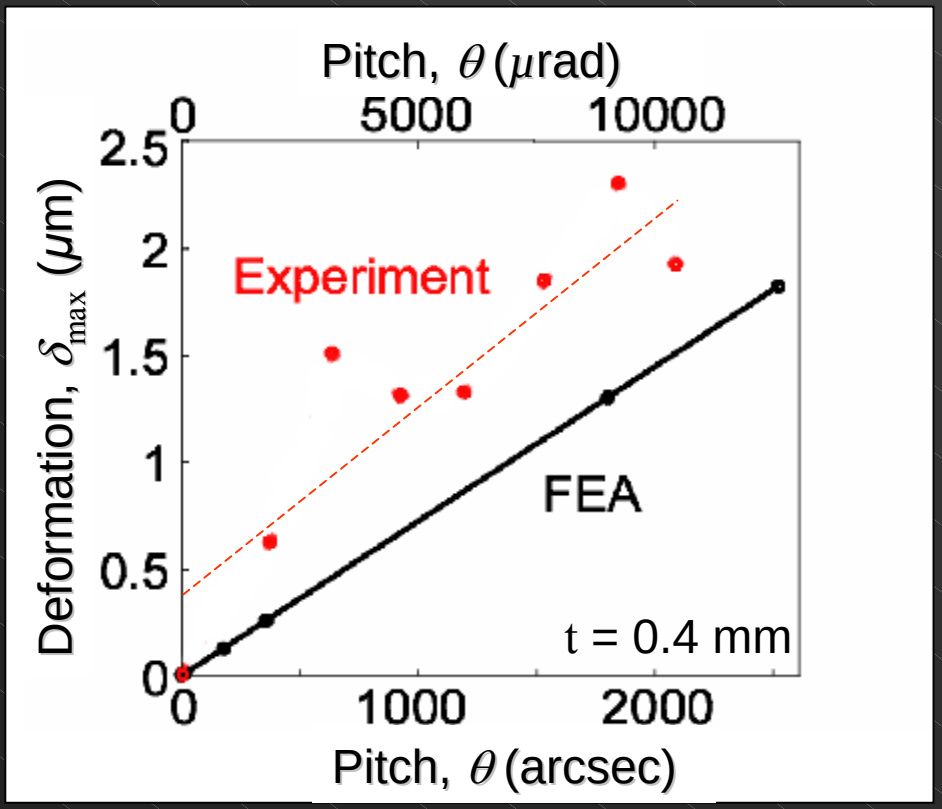
- Gravity sag
- Thermal expansion mismatch between foil and constraint device
- Friction from physical manipulation (i.e., assembly)



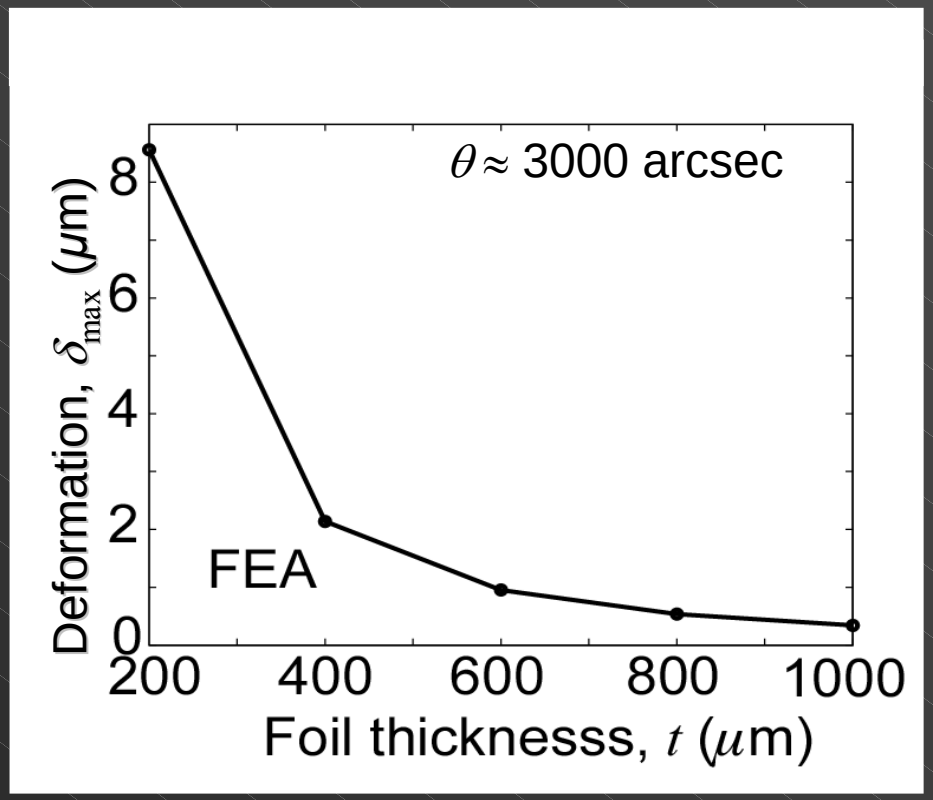
Gravity Sag

$$\delta_{\max} = \frac{\rho g \sin\theta L^4}{6.4 E t^2}$$

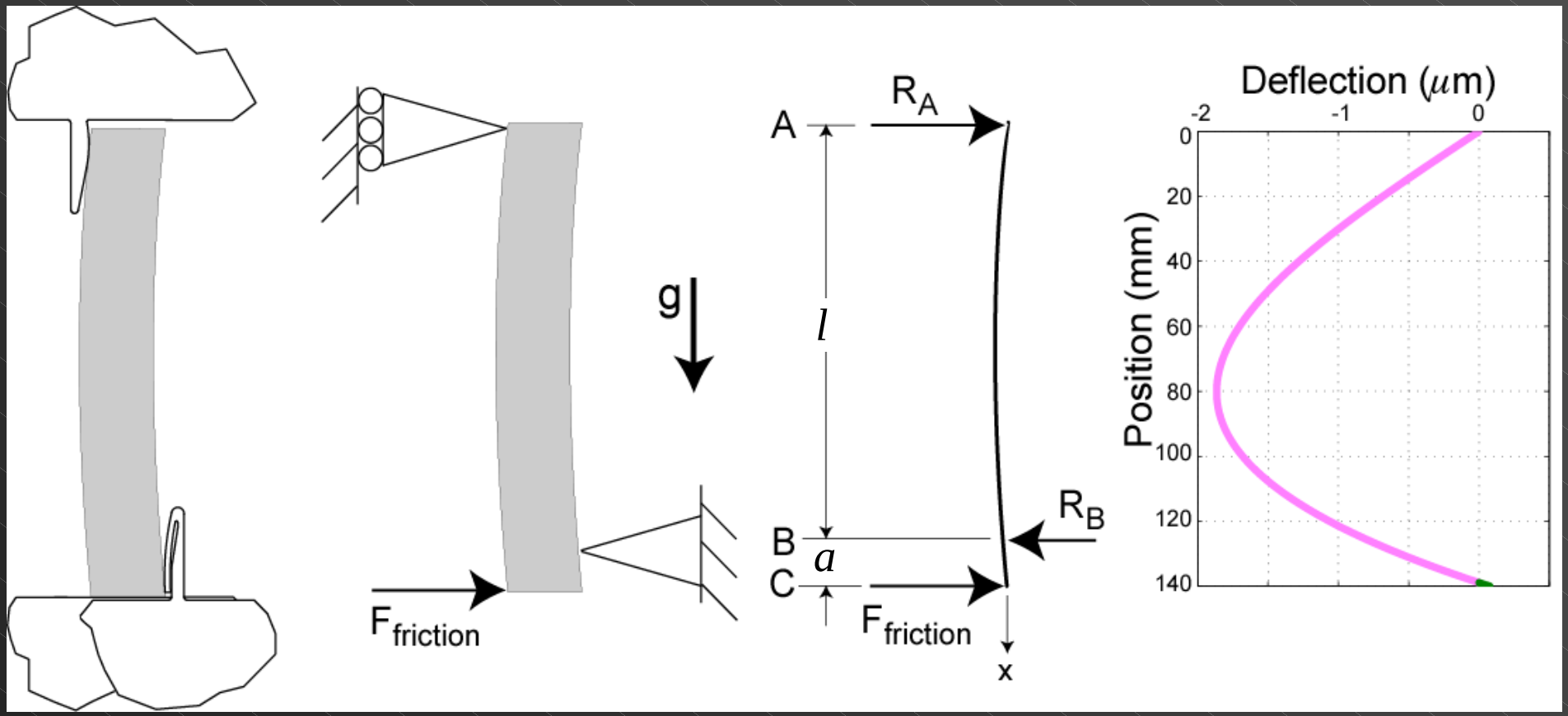
$\delta_{\max}$ vs. pitch angle



$\delta_{\max}$ vs. thickness



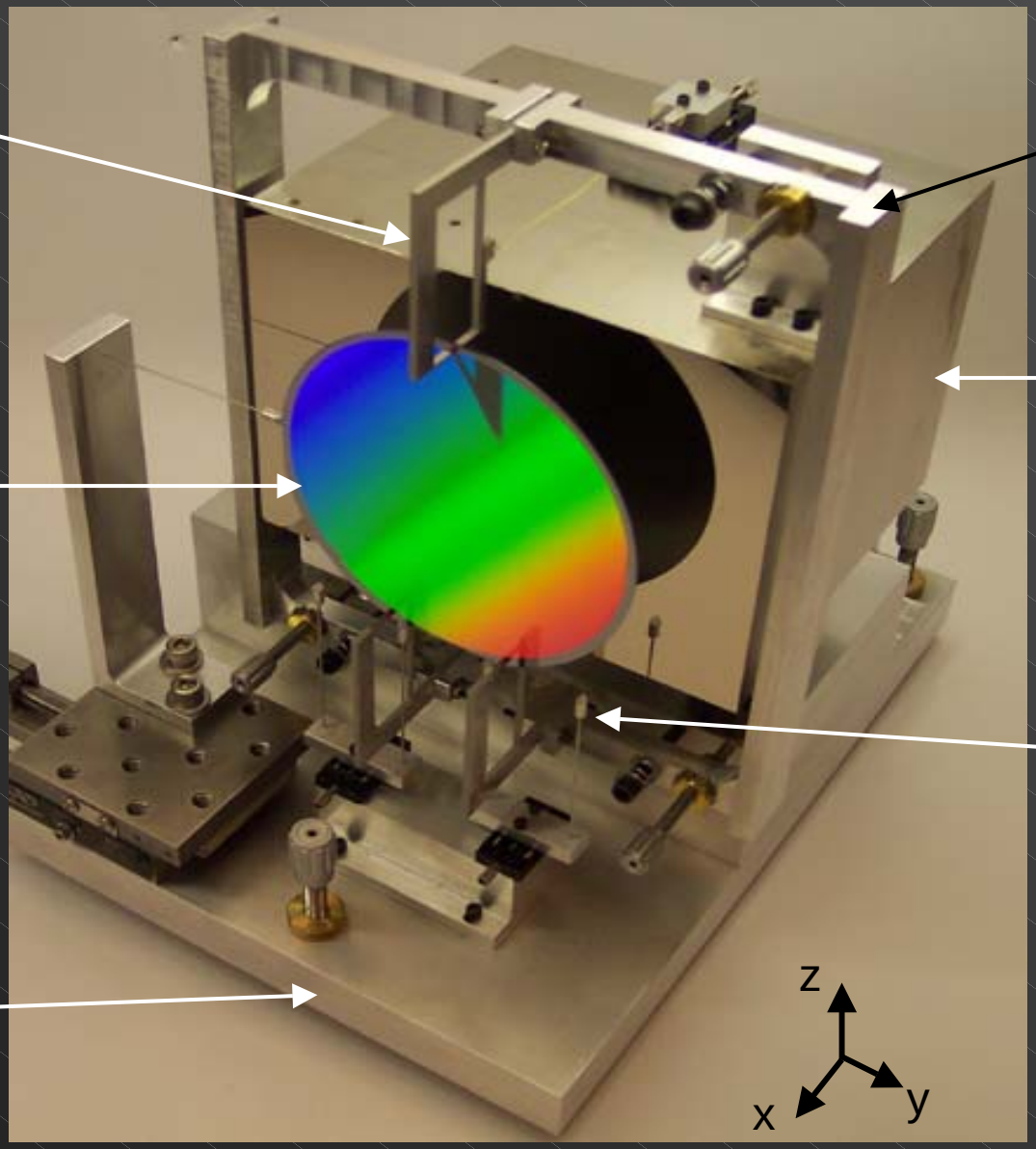
Friction Effects



$$\delta_{\max} = \frac{Fa^2(l+a)}{3EI} \text{ at } x_{\max} = \sqrt{\frac{l^2}{3}}$$

	$\delta_{\max}$ (μm)
Theory	1.91
FEA	2.76
Experiment	2.01

Thin Optic Metrology Truss



Double-sided flexures (3)

Vertical tilt stage

Reference block

Silicon wafer

Antenna flexures (4)

Horizontal tilt stage

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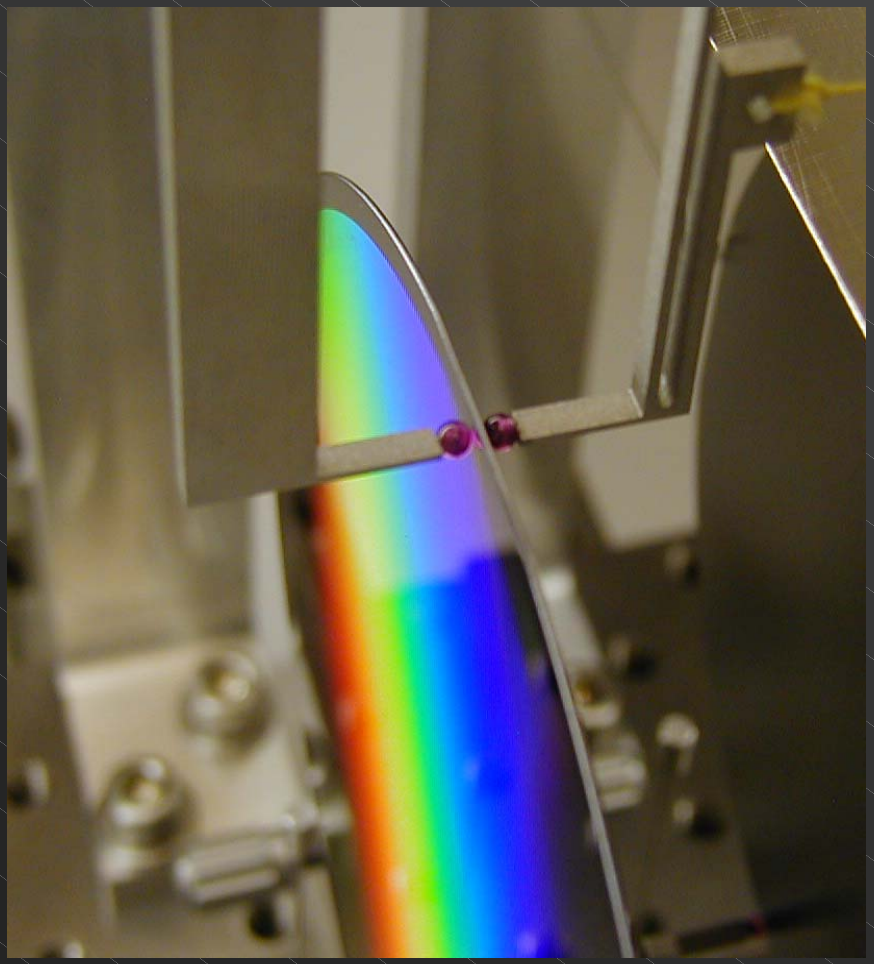
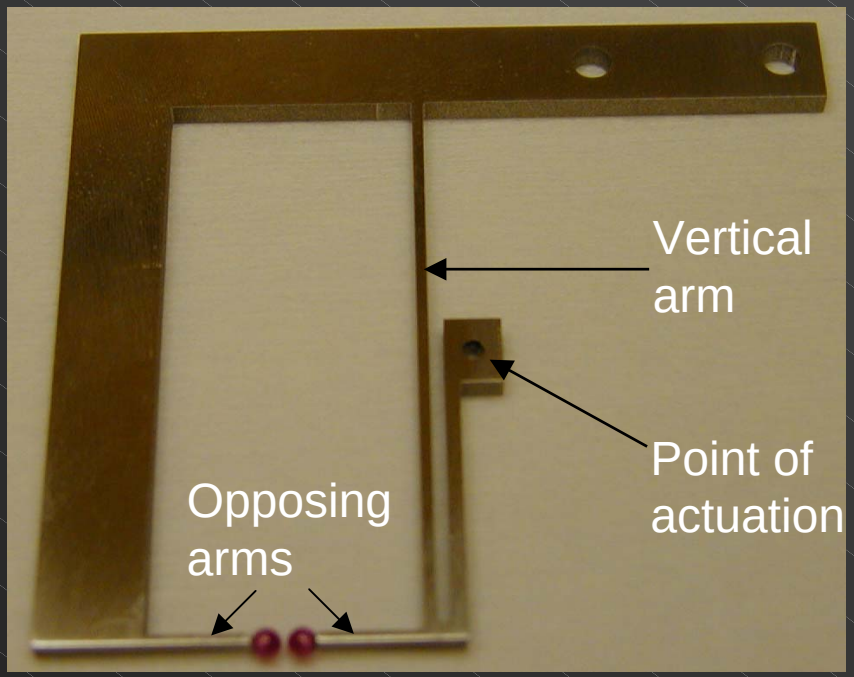
Monolithic Flexures

Double-sided flexures

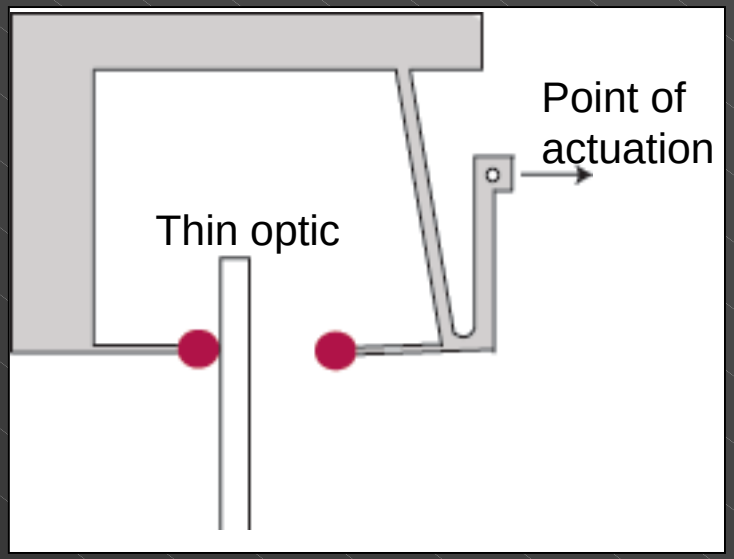


Antenna flexures

Double-Sided Flexure Design



Optic insertion/removal

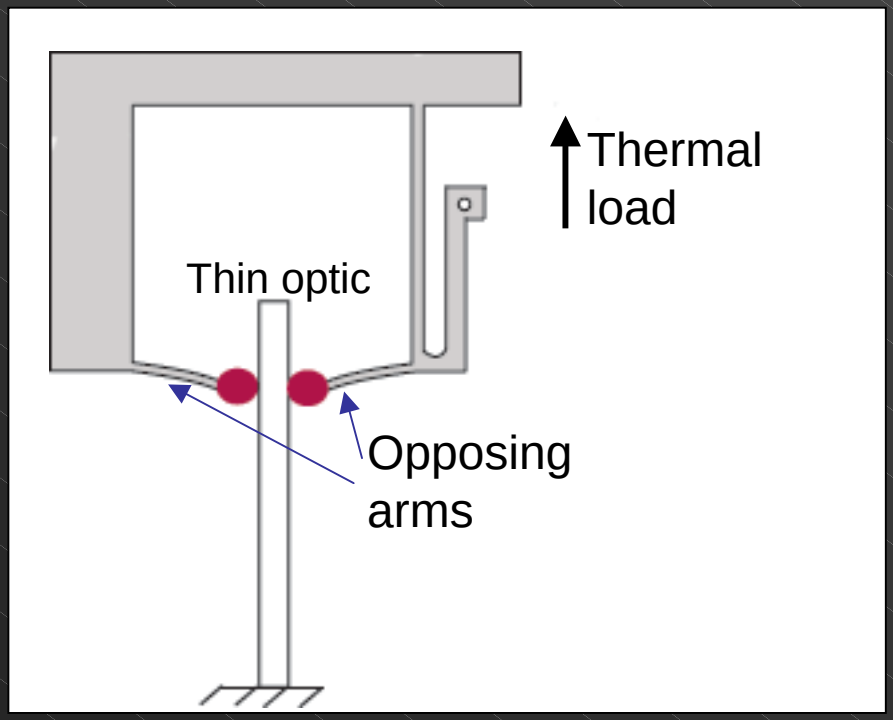


Vertical arm

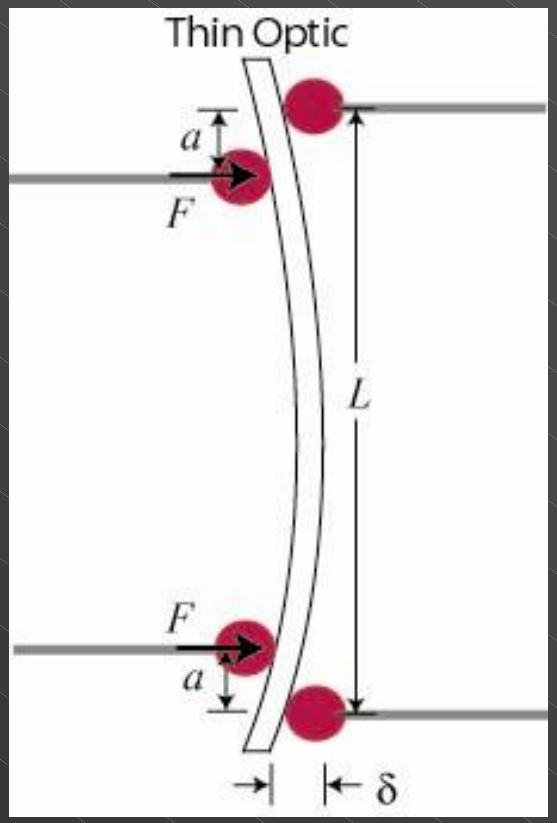
- Allow for optic insertion/removal
- Provide preload

Double-Sided Flexure Design

Thermal expansion compensation



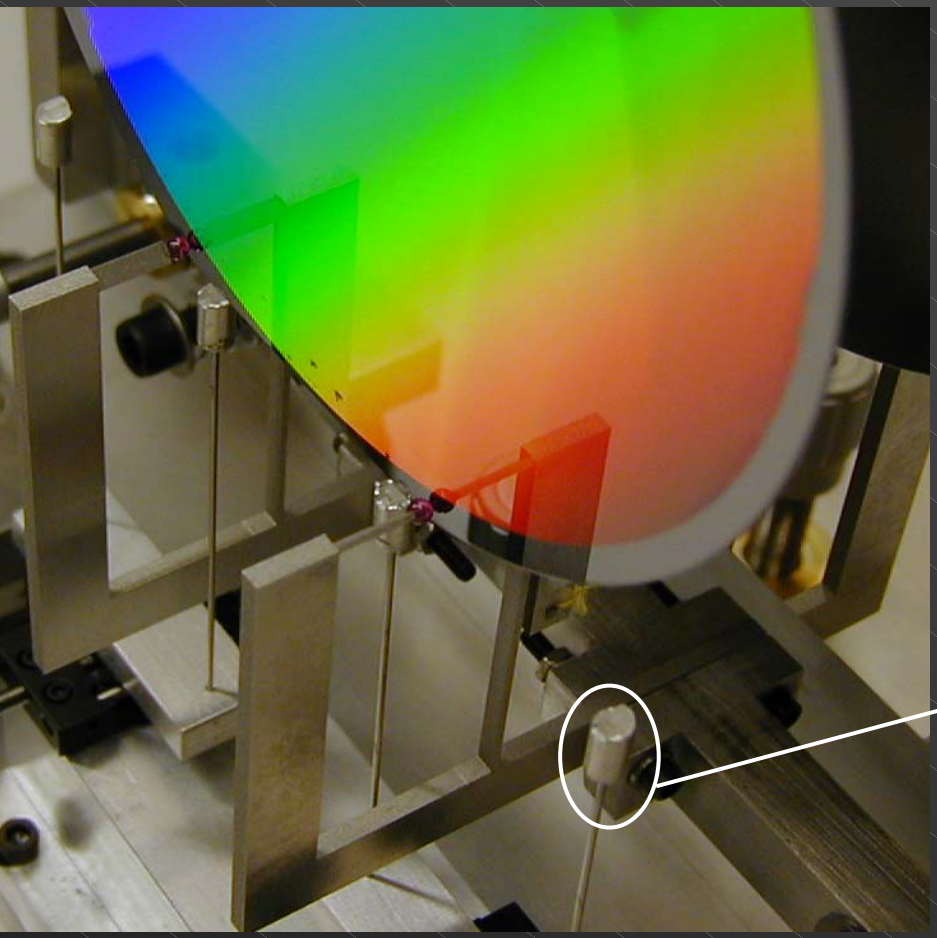
Opposing arm misalignment errors



Opposing arms

- Accommodate thermal expansion up to 1°C per measurement
- Manufactured using wire electric-discharge-machining of stress-relieved aluminum

Load Carrying Flexure Design



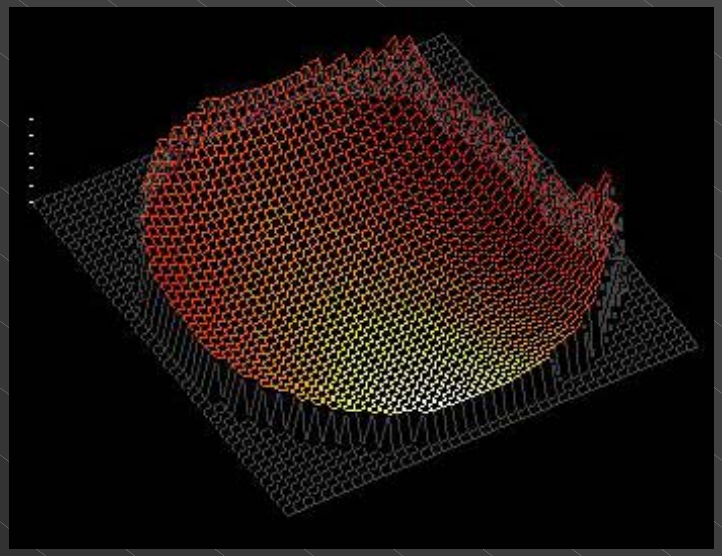
Sapphire tube to facilitate optic placement

Cylindrical flexure

Reduce friction-induced warp

Carry the load of optics up to 1.6 mm thick

Performance Evaluation



Metrology Truss repeatability (thin optic placed, removed and placed again) is 55 nm P-V

(Shack-Hartmann metrology tool repeatability is 36 nm)

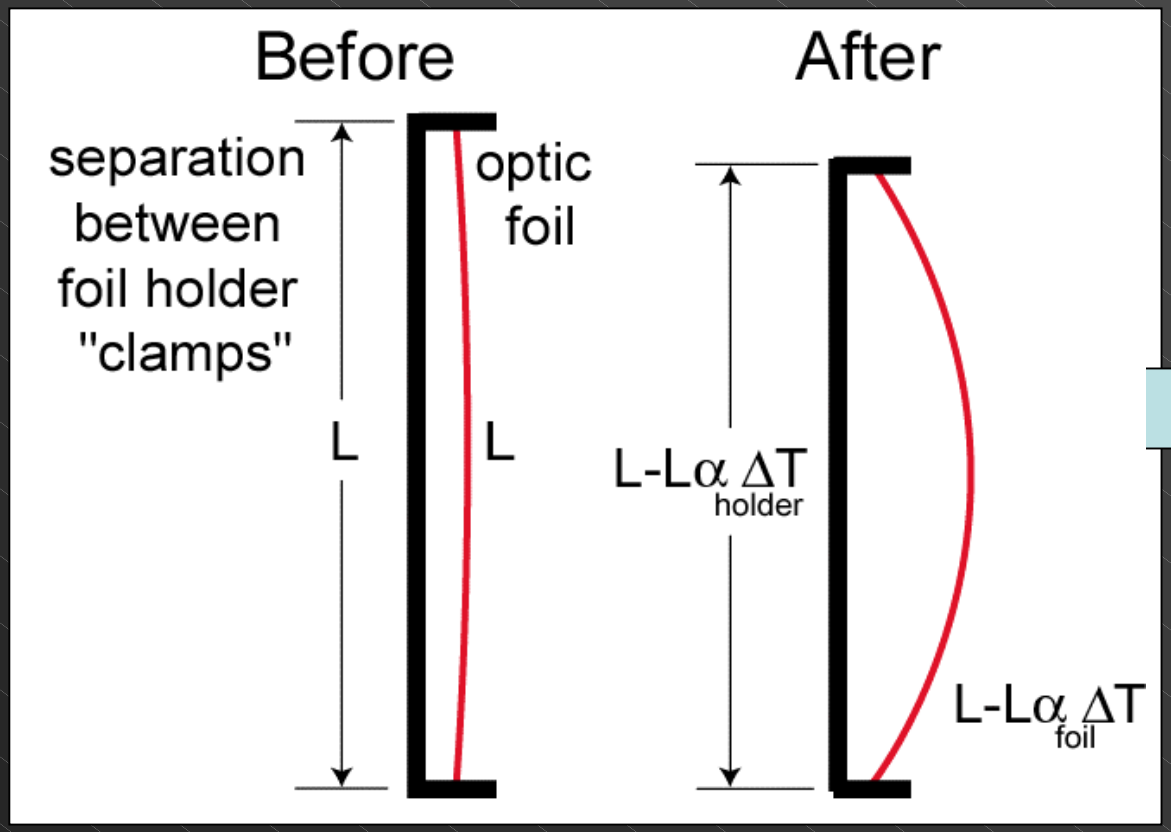
Conclusion

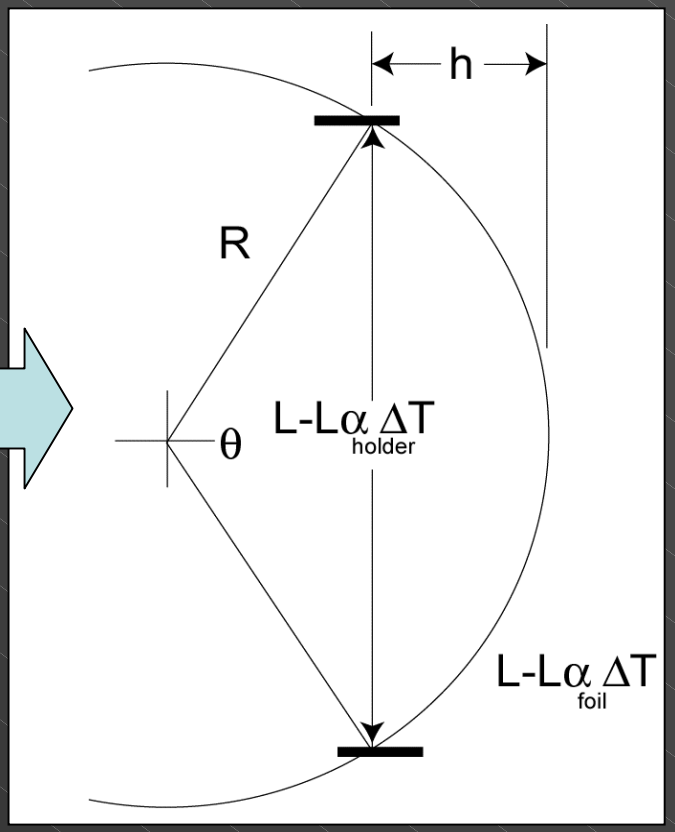
- Replicated 200 nm-period blaze gratings with thermal-cure and UV-cure process
- Extremely low out-of-plane distortion < 40 nm
- Thermally-imprinted grating has excellent diffraction efficiency, max ~43%
- Developed metrology truss to constrain thin optics
  - 55 nm repeatability

Acknowledgments

- A. Slocum, D. Trumper, C. Forest, A. Lapsa, V. Guillaume (Thin Optic Metrology Truss)
- M. Li (Nanoimprint process)
- A. Flanagan, A. P. Rasmussen, J. F. Seely, J. M. Laming, B. Kjornrattanawanich, and L. I. Goray (X-ray diffraction testing/simulation)
- NASA grants NAG5-12583 and NAG5-5405

Thermal expansion





$$\frac{2L}{L - L\alpha\Delta T} = \frac{L/R}{\sin(L/2R)}$$

$$h = R - R\cos(L/2R)$$

$\Delta T = 1^{o}\mathrm{C}$

$L = 140$ mm

	α_{th} (10^{-6}/°C)	h (μm)
Glass	6.3	350
Si	3.7	377

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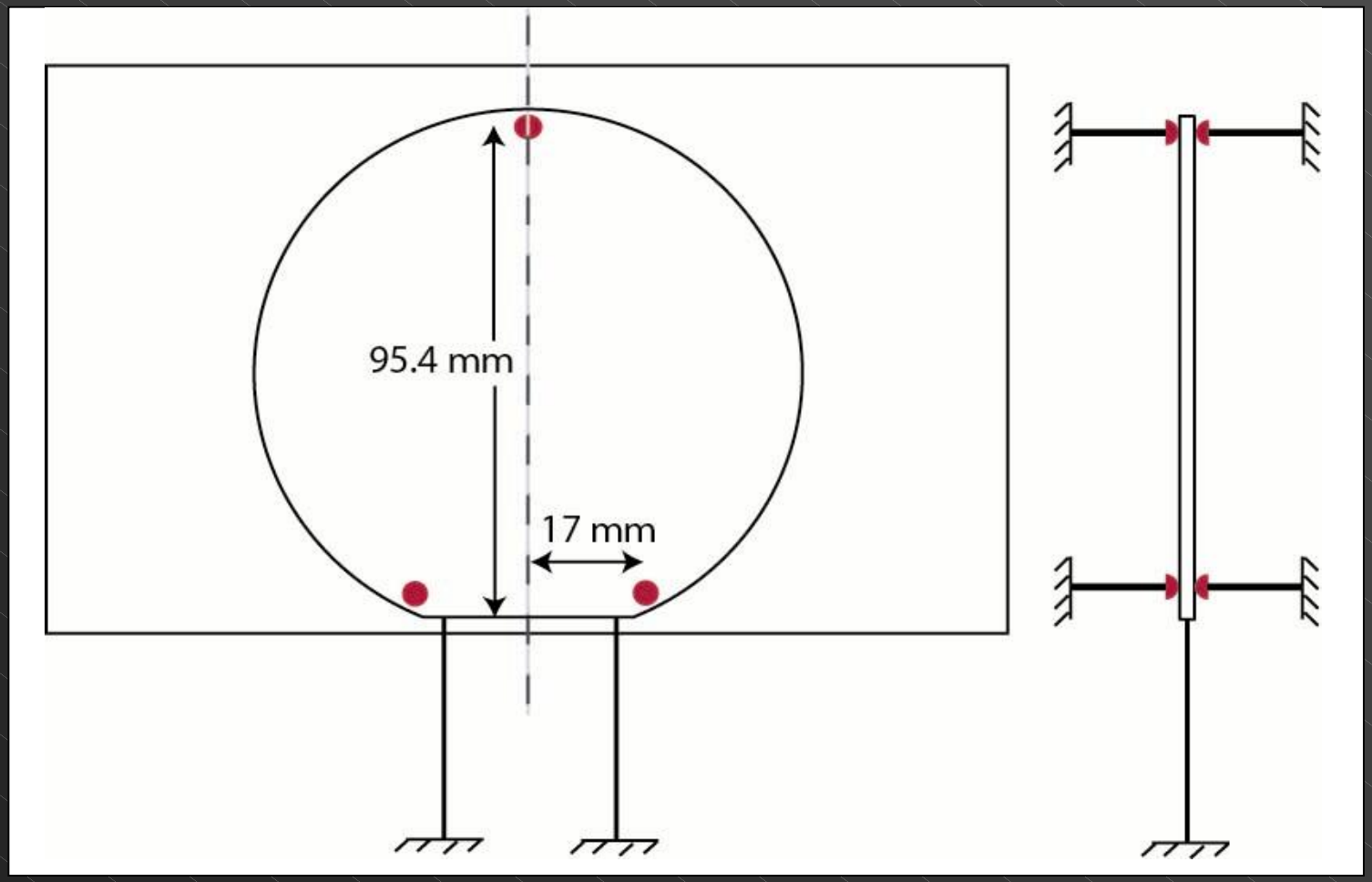
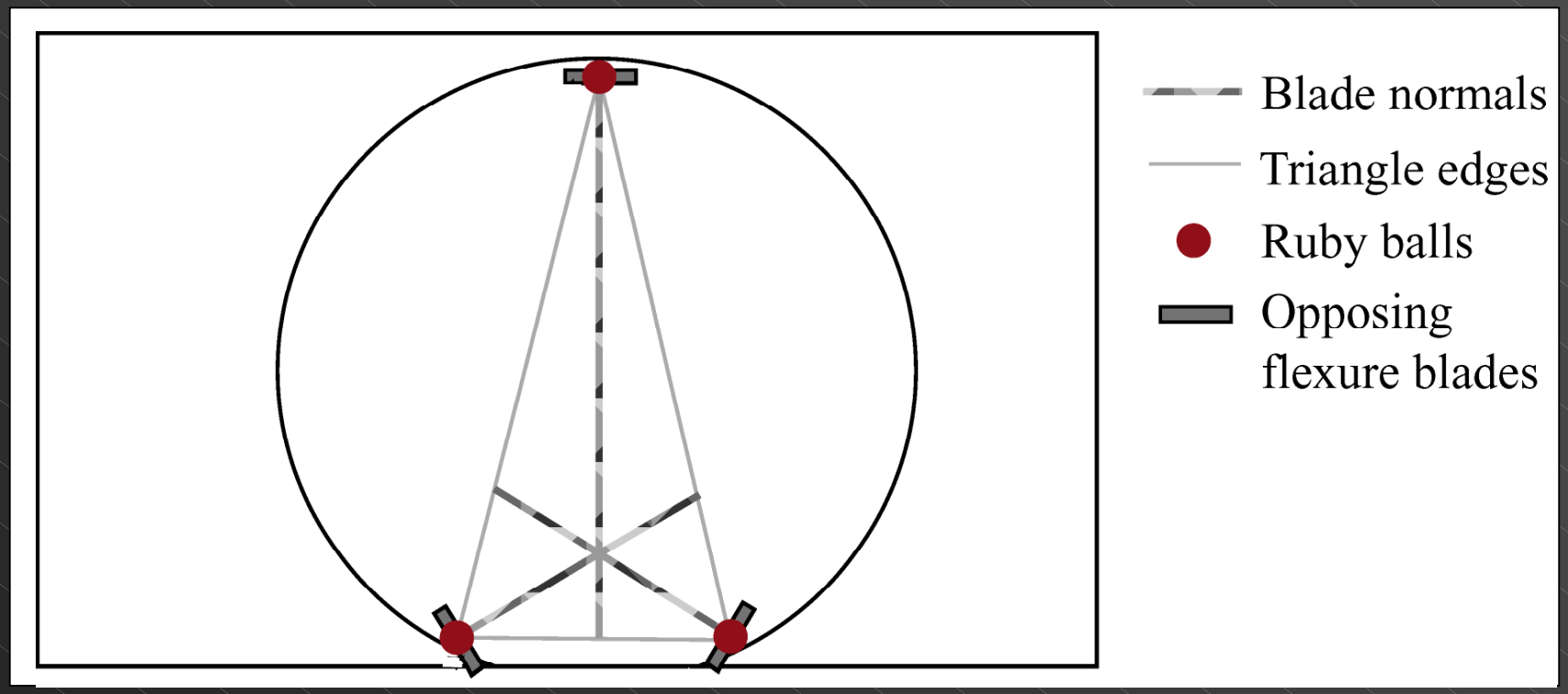
Thermal Lengths



Double-Sided Flexure Performance



Temperature variation of 1.2°C during 3 hrs

Maximum deformation 92.5 nm

Double-Sided Flexures

Design Analysis

Wire EDM-ed, Monolithic flexures

1. Vertical flexures

   Allow for optic insertion/removal

   Provide preload

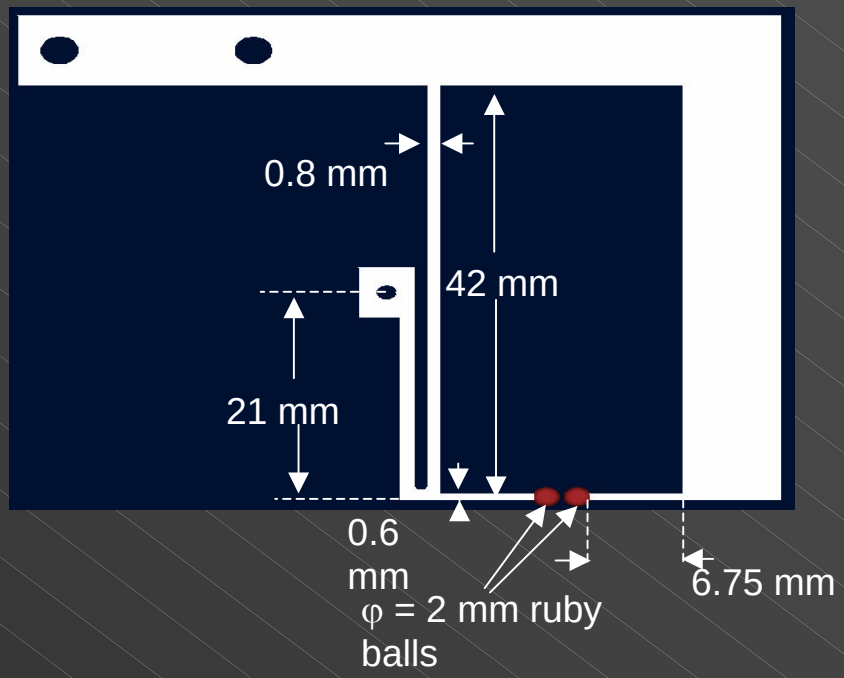
   ($k_{lateral}$ = 2.45E-4 N/μm)

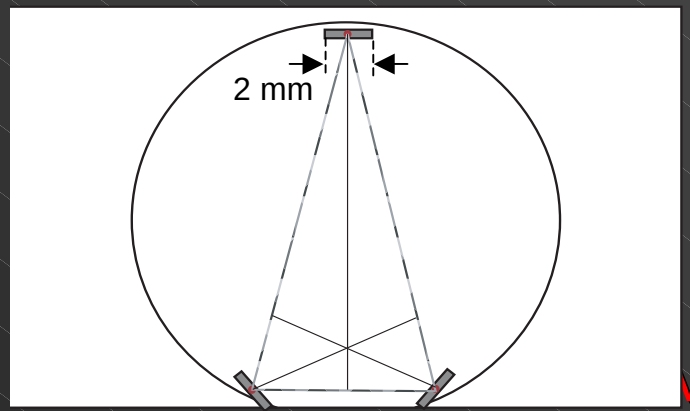
2. Horizontal flexures

   Accommodate for thermal expansion

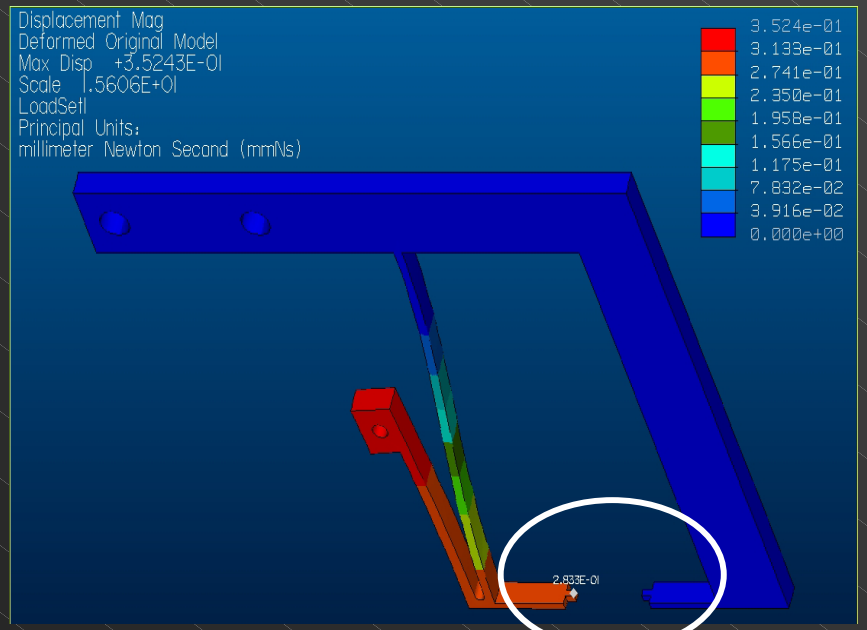
   ($k_{lateral}$ = 0.024 N/μm)

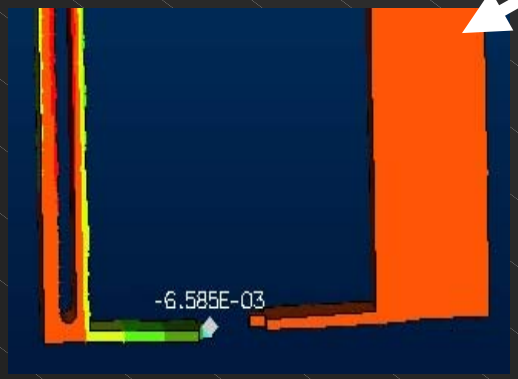
Material Aluminum 6061 T651





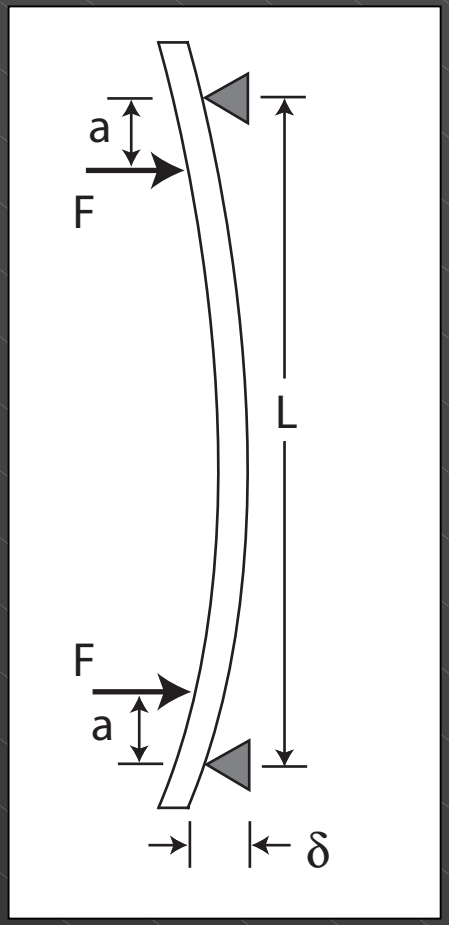
Monolithic Flexure Errors





Vertical parasitic motion

$$\delta = \frac{Fa\left(3L^2 - 4a^2\right)}{24EI}$$



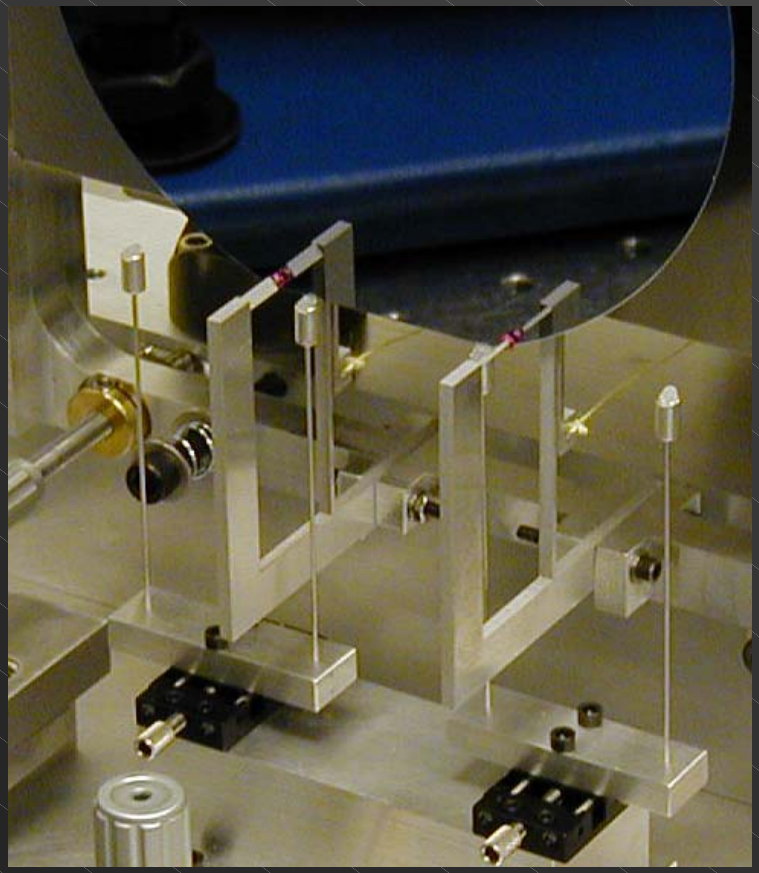
After optic placement

x = 283 μm

a = 6.6 μm

F = 0.067 N

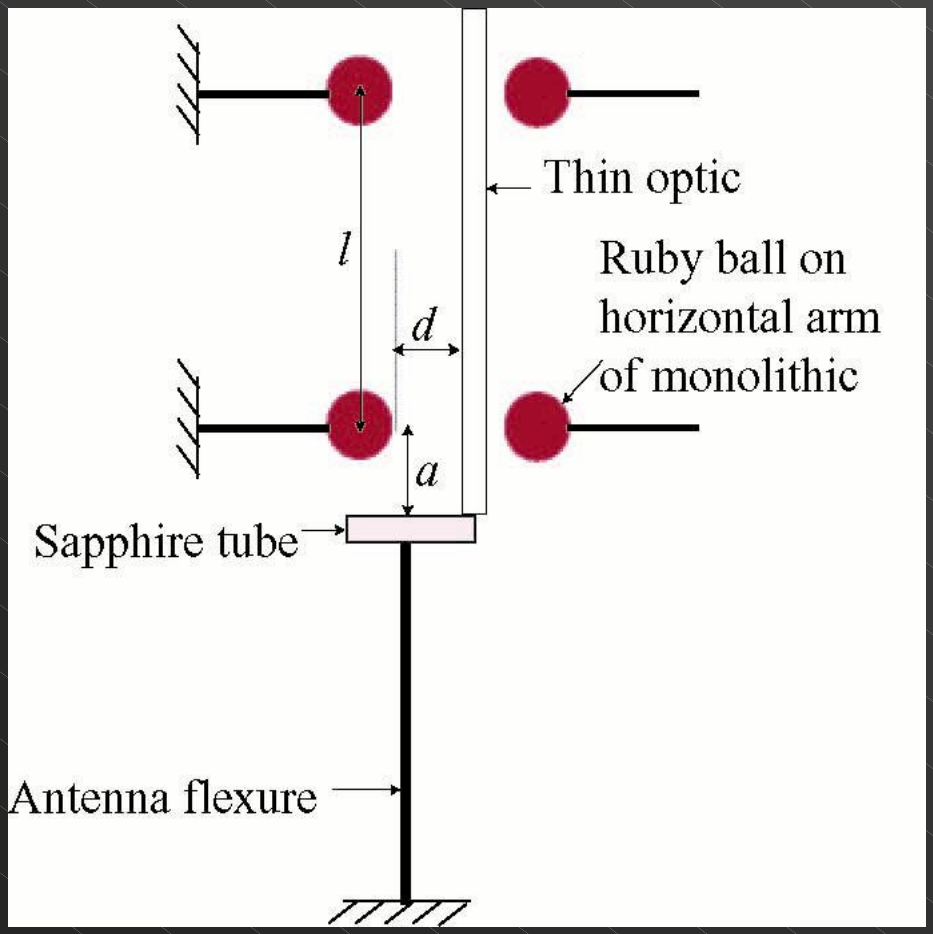
δ = 8.65 nm

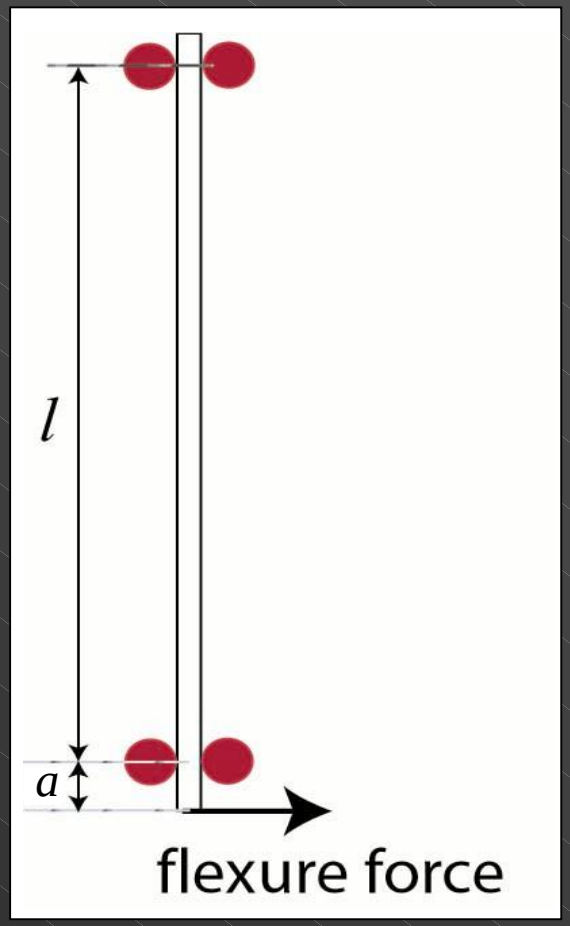


SNL

MIT

Errors Induced by Antennas





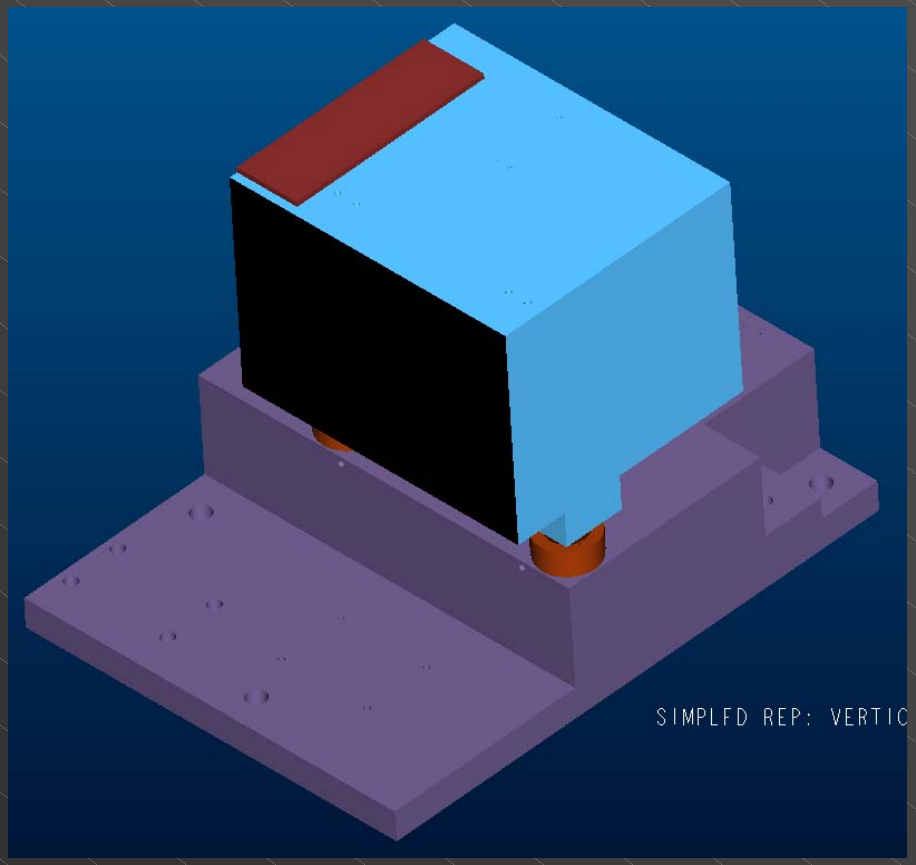
$$\delta_{\max} = \frac{Fa^2(l+a)}{3EI} = 148nm$$

SNL

MIT

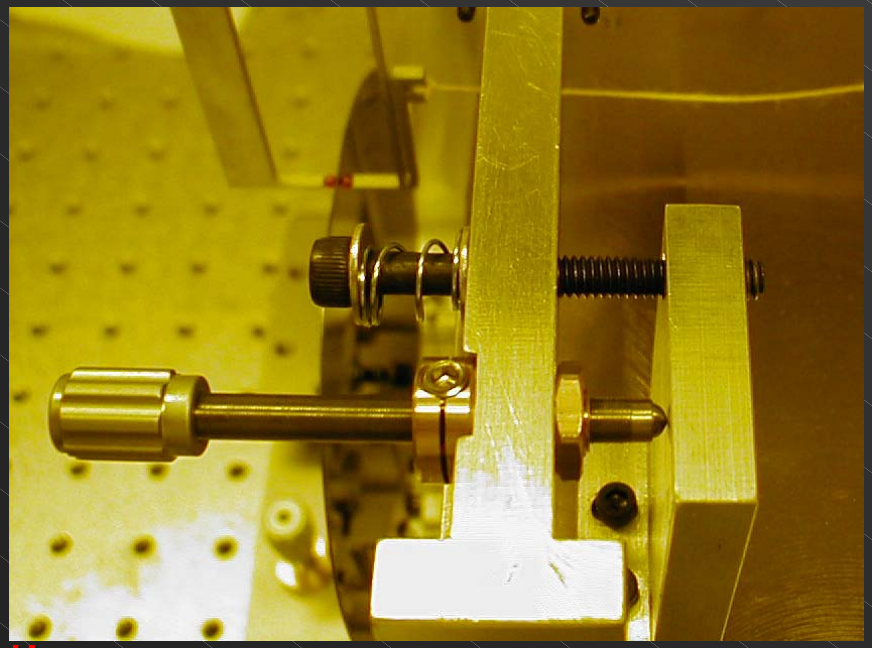
Vertical Reference Flat

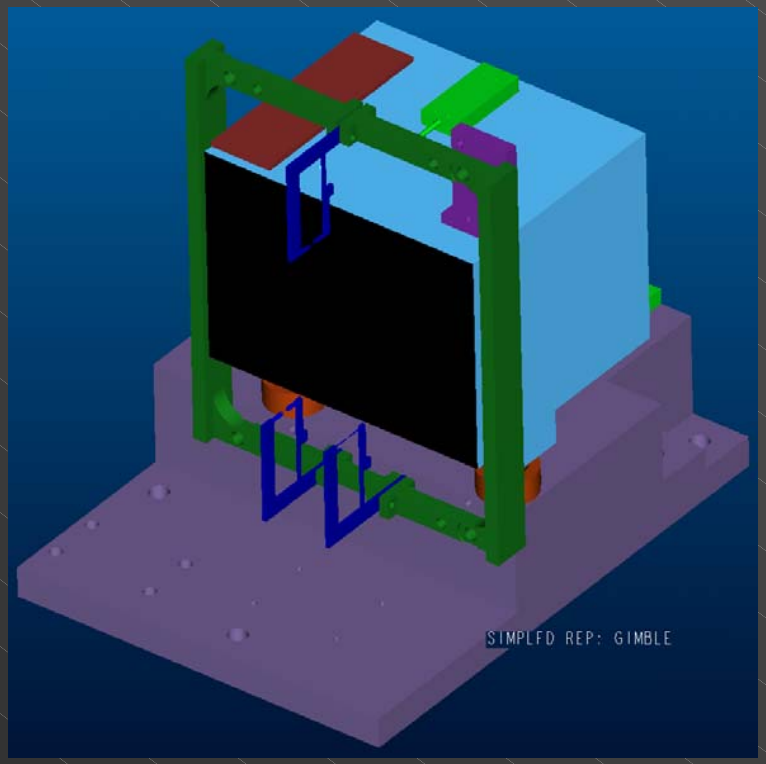
- Front surface flatness: 0.1um
  - Optically polished Nickel coated Aluminum block
  - 90 deg Angle +/- 1 arcsec
- Base has tilt adjustment
  - Resolution: 2 μrad
- Inclinometer resolution: 14 arcsec



Flexure Tilt Stage Design

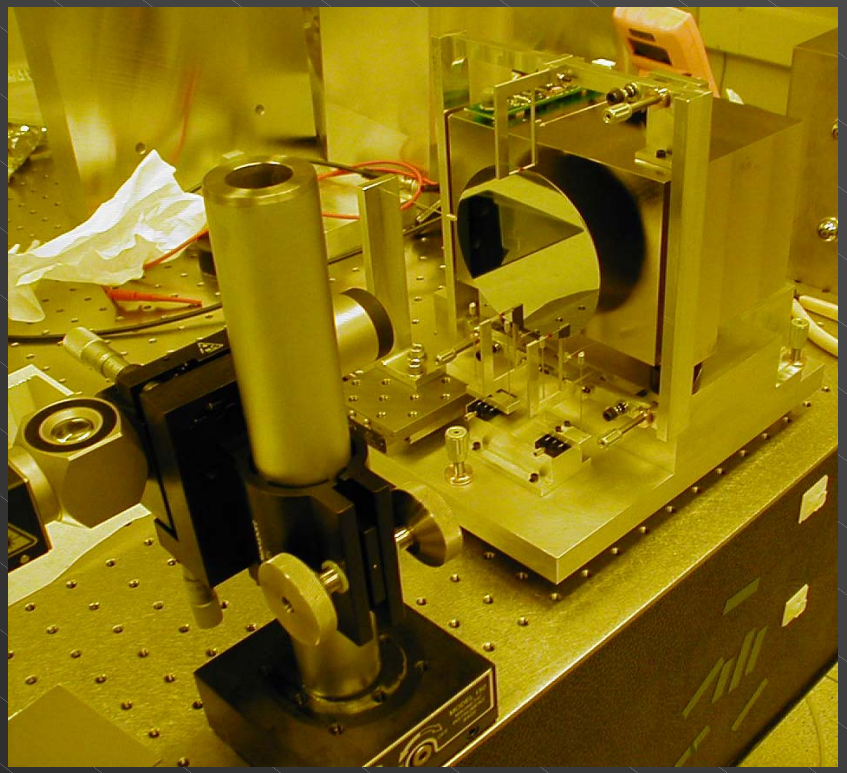
- Allows for pitch / yaw adjustments (2 ± 0.0005°)
- Actuation Mechanism:
  - Fine-thread (#¼-100) screws
- Preload Mechanism:
  - Springs





Preliminary Experiments

- Autocollimator Experiments:

• Flexure tilt stage:
achieves desired range & accuracy (2 μrad)

• Repeatability
  Pitch: 1.2 μrad
  Yaw: 11 μrad