Recent development of light-weight & high-resolution X-ray optics in Japan

Yuichiro Ezoe

Tokyo Metropolitan University (TMU)

AXRO 2009

Outline

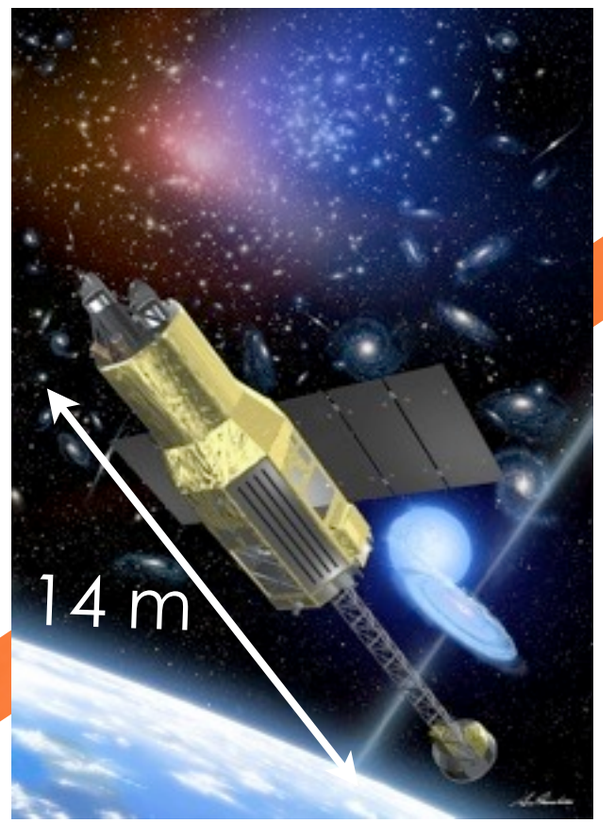
- Target missions
- Recent development of our optics
  - 1. MEMS X-ray optics
  - 2. Plastically shaped Si optics

Future missions

- Astro-H (2013, J-US-E)

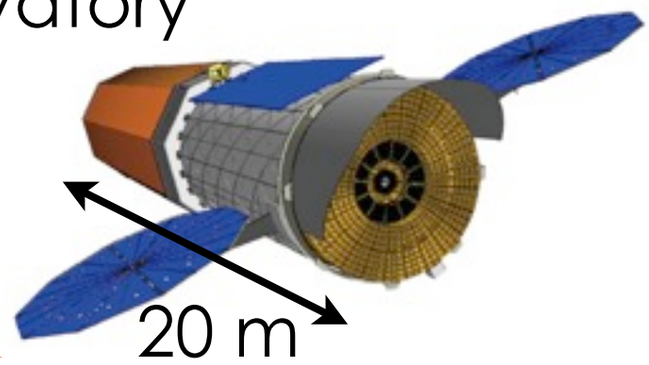
  Observatory
  Hard X-ray Telescope
  Microcalorimeter
  X-ray CCD, etc...

Suzaku



- IXO (~2022, E-US-J)

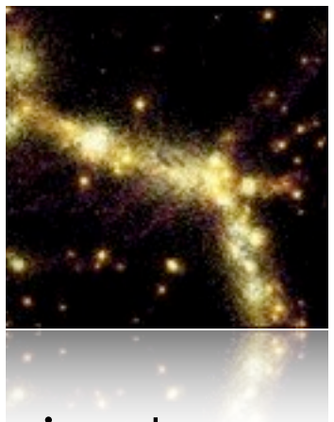
  Observatory



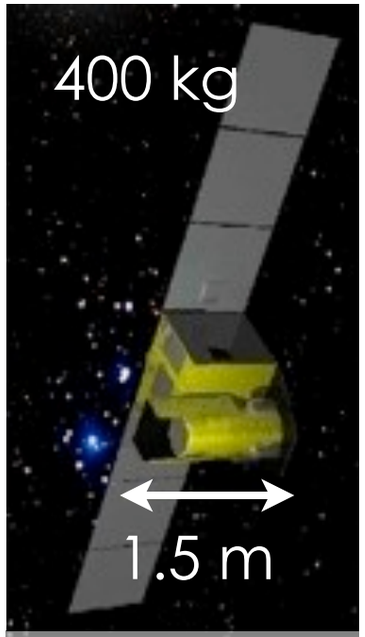
- MAXI (2009)
  All Sky Monitor
- NuStar (2011)
  Hard X-ray Telescope
- SRG (2012)
  X-ray Survey
- GEMS (2014)
  Polarization

Small but unique

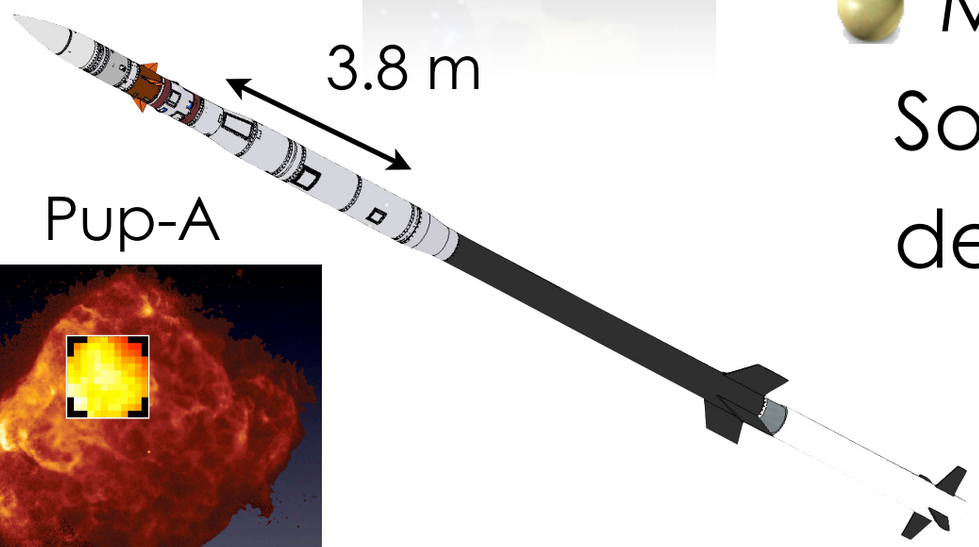
90 M light year



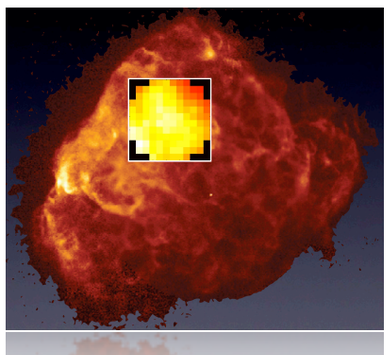
missing baryons



Payload 520 kg



Pup-A



- DIOS (2015, Japan)
  JAXA small satellite series
  large field of view telescope
  microcalorimeter

  4-stage optics, 0.2-1.5 keV,
  f=0.7 m, $\Delta\theta < 2'$, $S\Omega$ >100 cm^2 deg^2

- Micro-X (2011,12 ..., US)
  Sounding rocket experiment
  demo of microcalorimeter for IXO

  Wolter-I optics, 0.2-3 keV,
  f=2 m, $\Delta\theta < 2'$, $S > 200$ cm^2

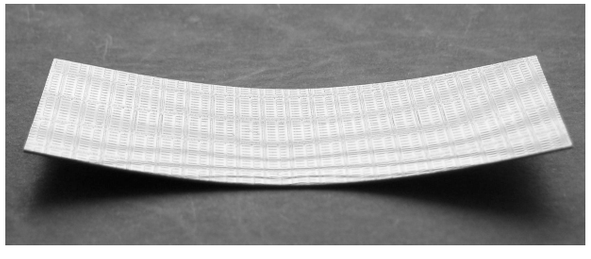
How to diet ?

- **1. Stiff mirror substrates**
  - Glass sheet, Si wafer
  - ~2.5 g/cc
  - flatness : <1 μm
  - smoothness : <1 nm

Glass sheet

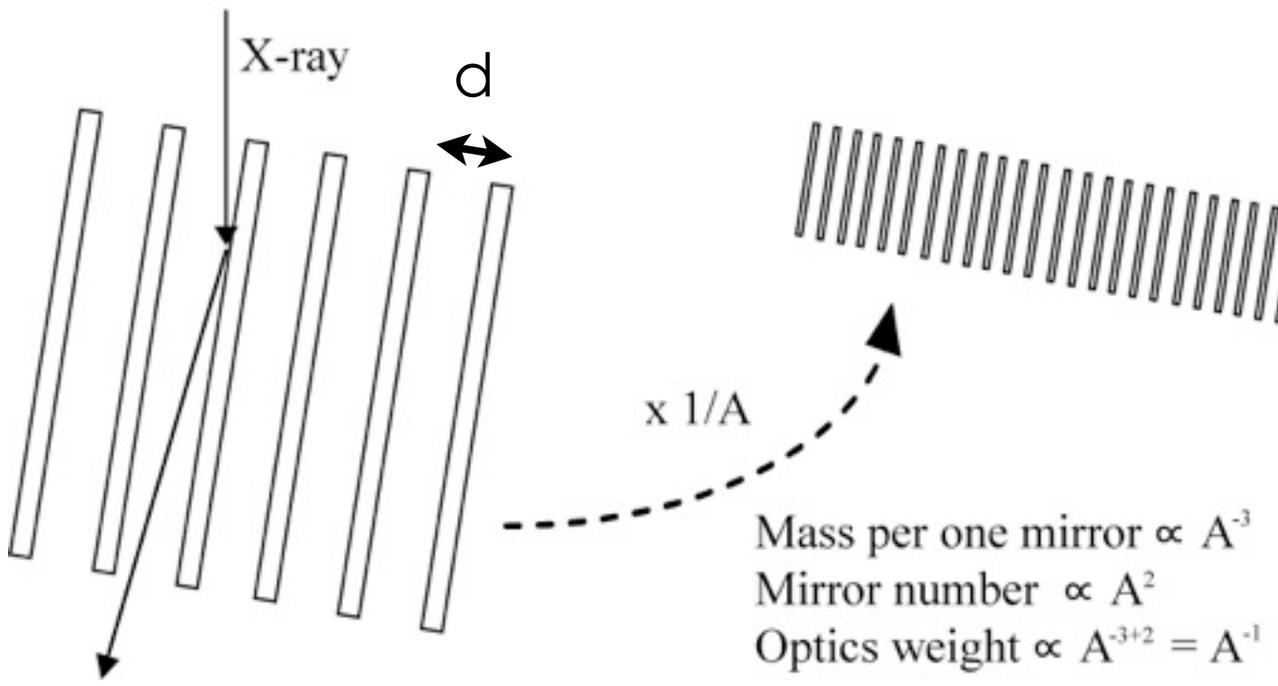
Zhang+07 SPIE,
Ghigo+06 SPIE
Friedrich+05 SPIE
Hudec+06,07,08 SPIE

Si wafer



Hudec+06,07,08 SPIE
Ezoe+09 SPIE

- **2. Micro pore optics**



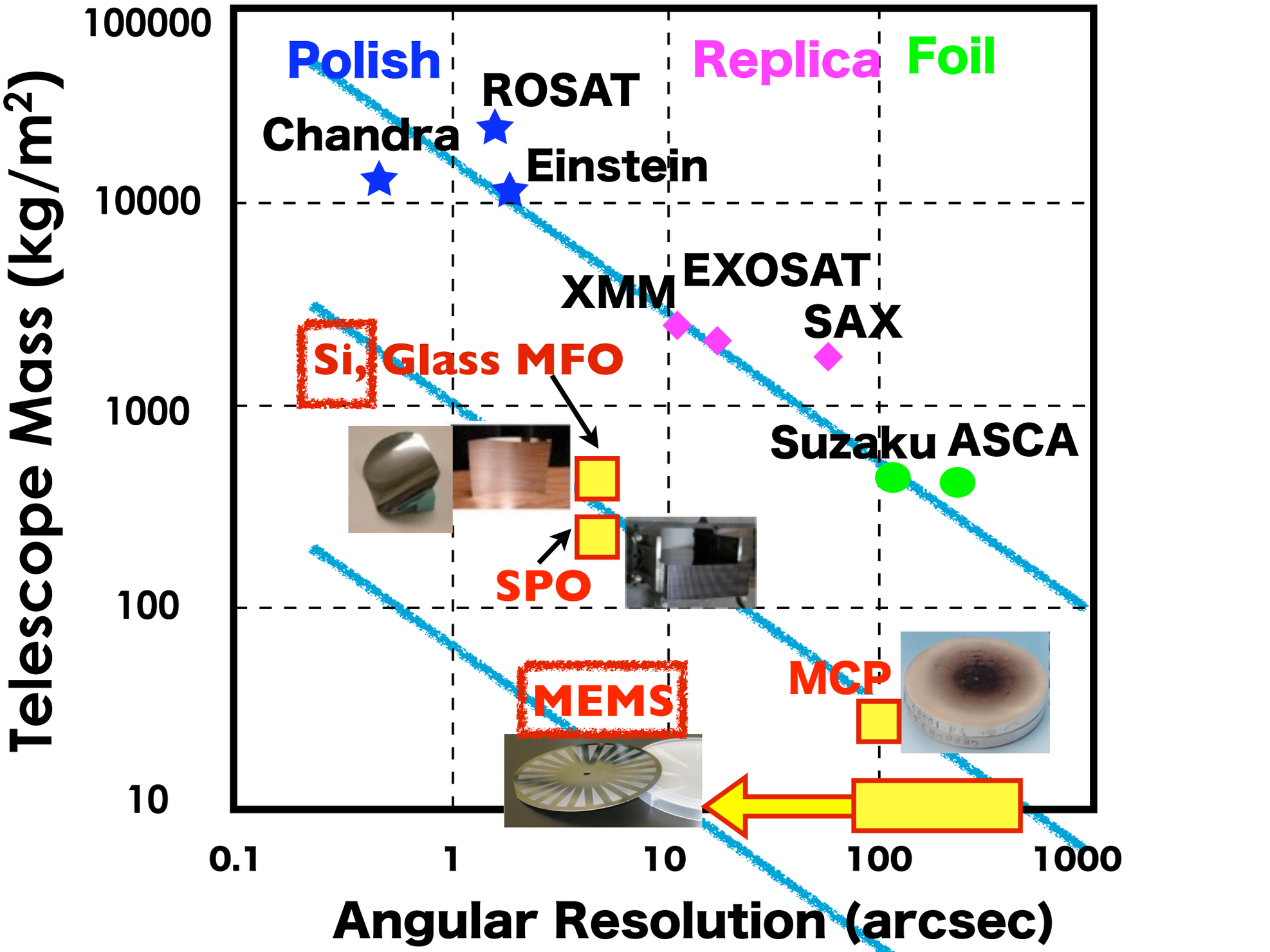
- **X-ray diffraction**

$$\Delta\theta \sim \frac{d}{\lambda} \sim 13'' \left(\frac{d}{20\ \mu\mathrm{m}}\right) \left(\frac{E}{1\ \mathrm{keV}}\right)$$

limits size reduction

Objectives

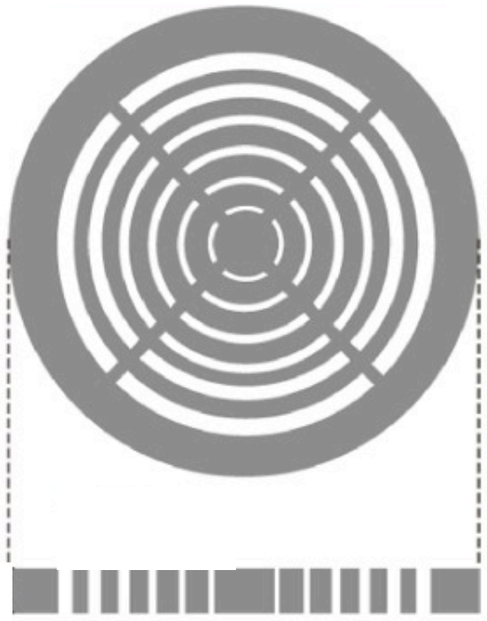
Bavdaz+04 SPIE (revised)



* Micro Electro Mechanical Systems

1. MEMS* X-ray optics

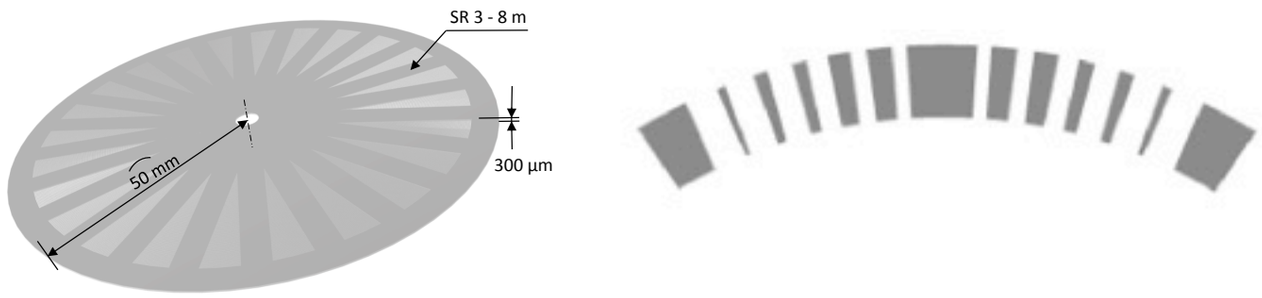
1. concentric micro pores



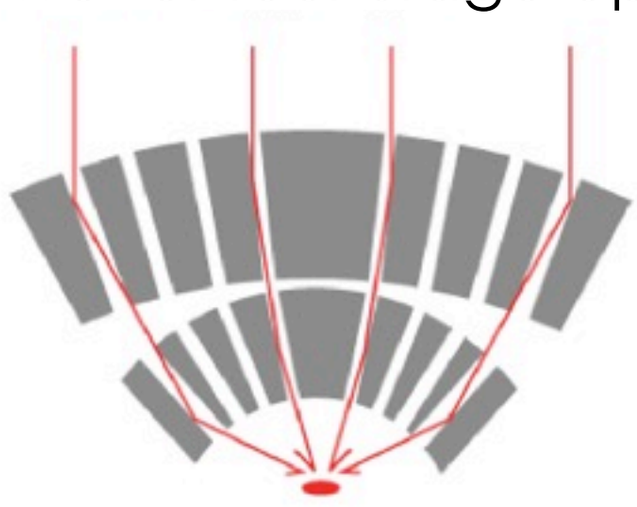
2. finishing side walls

rms roughness < 3 nm

3. spherical deformation



4. two- or four-stage optics



- **Mass : on the order of 10 kg/m^2 (← ~20 μm width pore)**
- **Angular resolution : ~15 arcsec (← diffraction at 1 keV)**
- **Filling factor : >50 %**
- **Manufacturing cost saving**

(Ezoe+08 AXRO, Mitsuishi+09 SPIE patent pending)

Elemental technologies

step1: Curved micro pore structure

Silicon DRIE
(Si structure)

X-ray LIGA
(Ni structure)

step2: Finishing sidewalls

Hydrogen annealing
(Smoothing Si)

Magnetic field
assisted finishing
(Polishing
Si & Ni)

step3: Spherical deformation

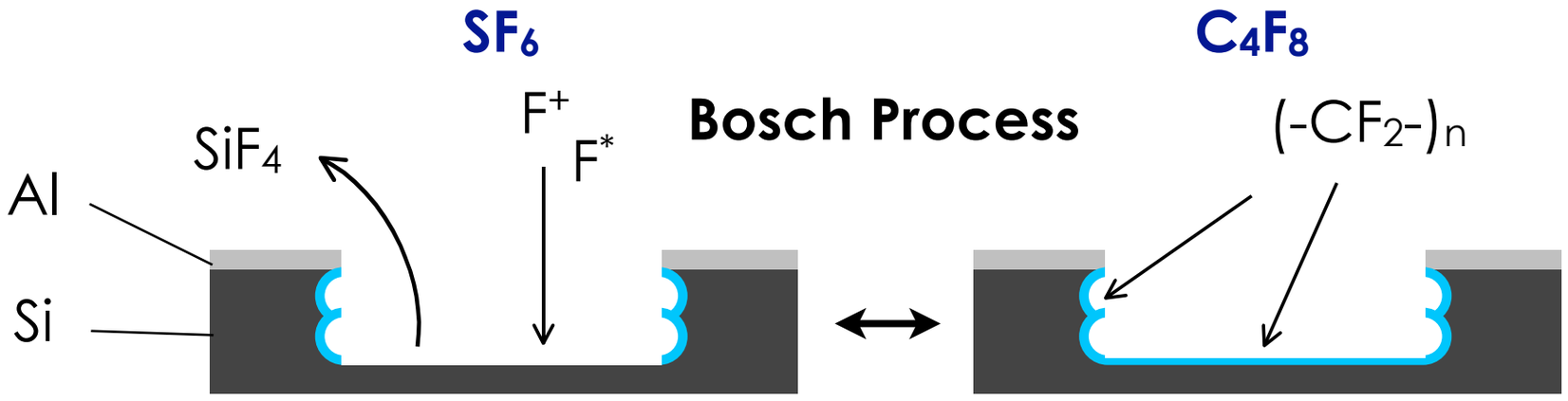
Hot plastic
deformation
(Si)

Elastic
deformation
(Ni)

Step 1 : Microstructure fabrication

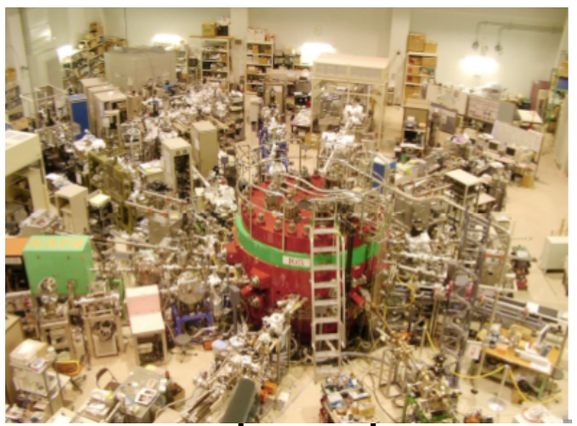
- Deep Reactive Ion Etching (DRIE)

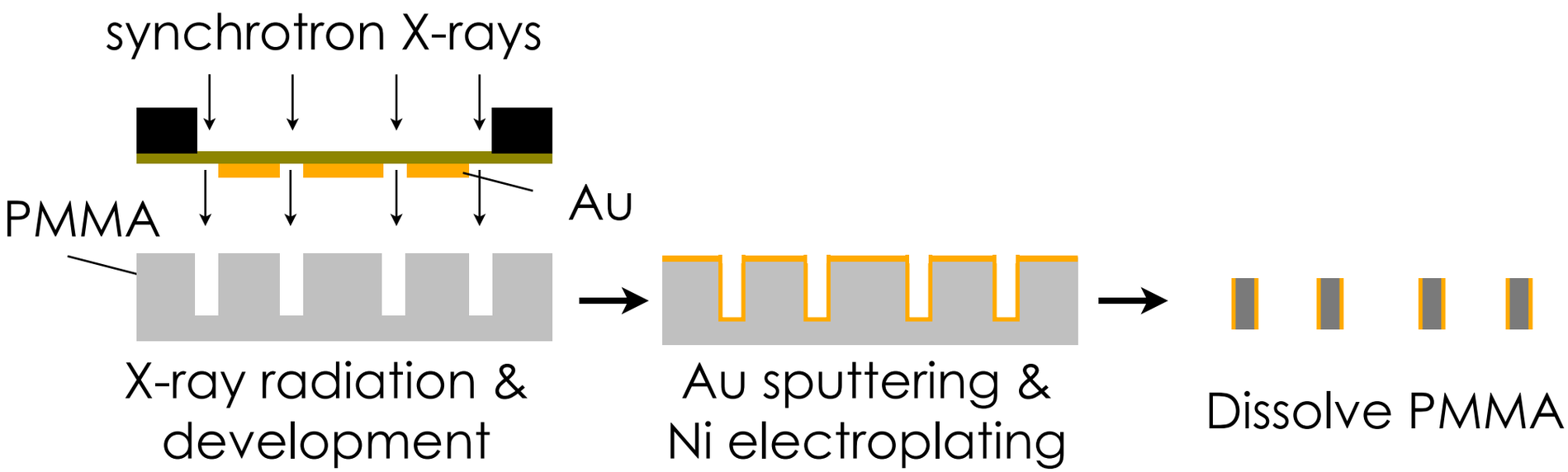
DRIE machine @ ISAS



- X-ray LIGA (lithography and electroplating)

AURORA @ Ritsuemikan





DRIE-fabricated Si optics

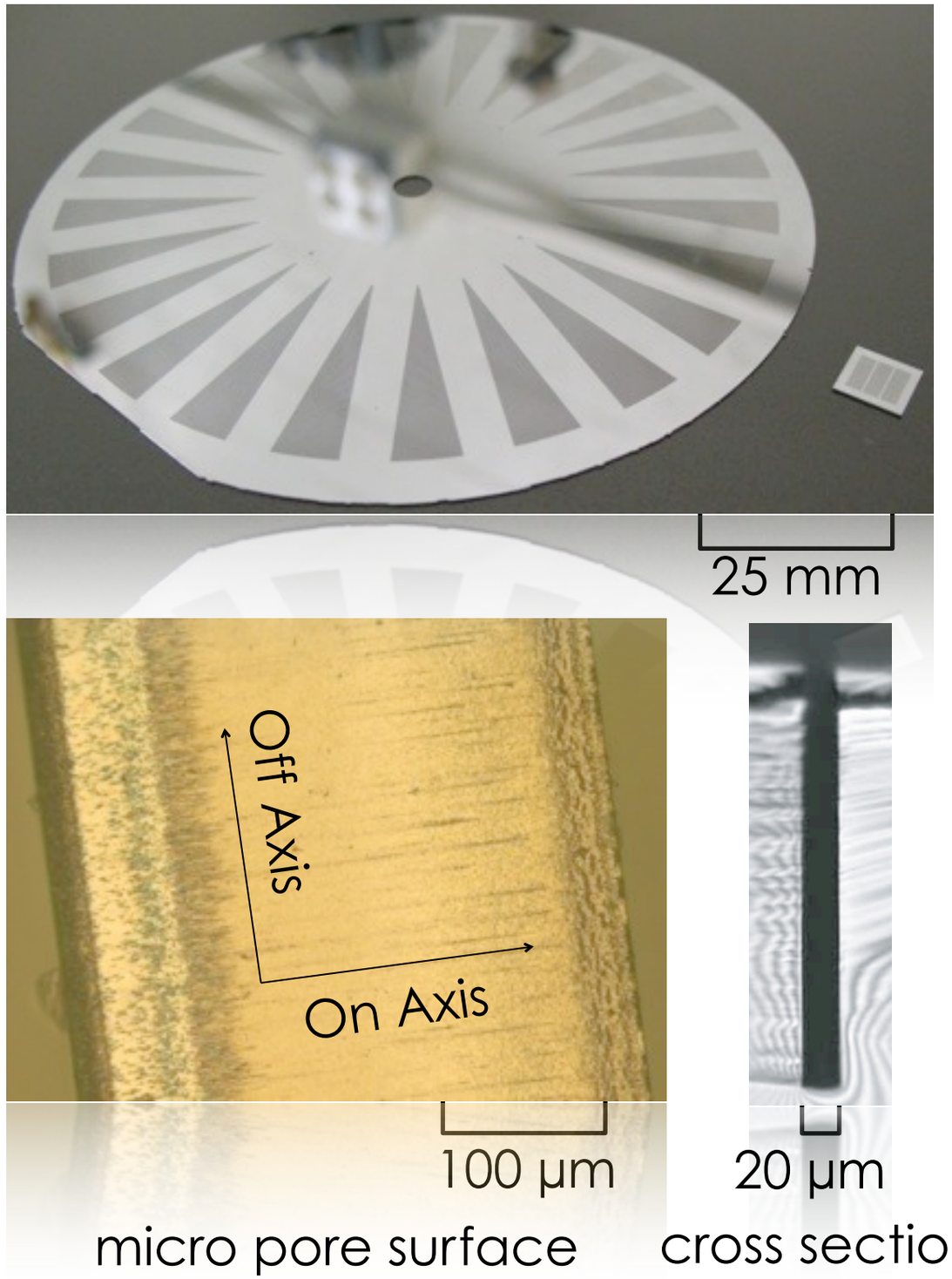
- Silicon
- High aspect ratio :

  ~30
- Working area :

  ϕ 4 inch
- Micro roughness :

  ~30 nm rms @ Off axis

  ~10 nm rms @ On axis



LIGA-fabricated Ni optics

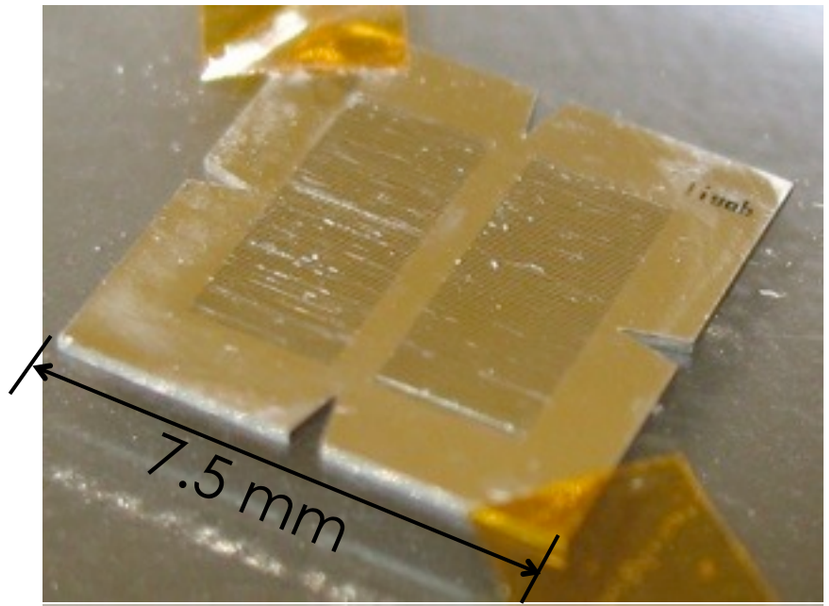
- Nickel
- High aspect ratio :

  ~100
- Working area :

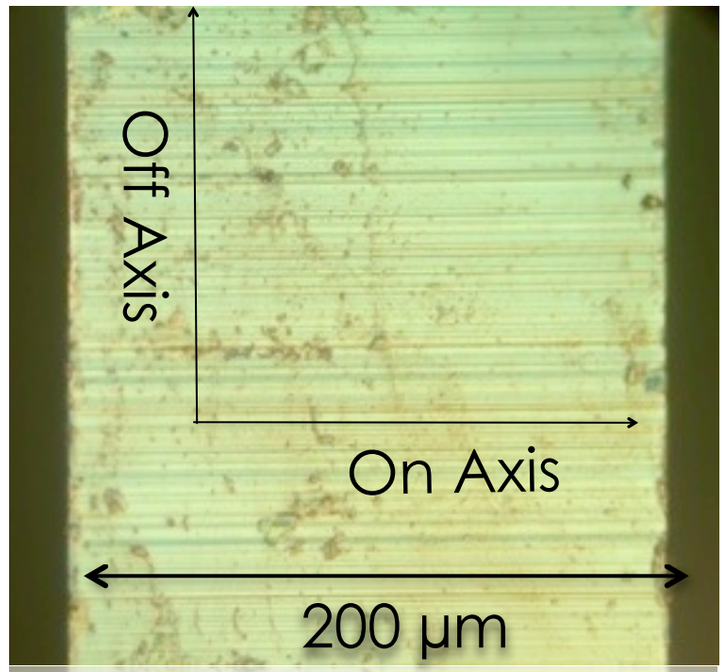
  35x100 mm^2
- Micro roughness :

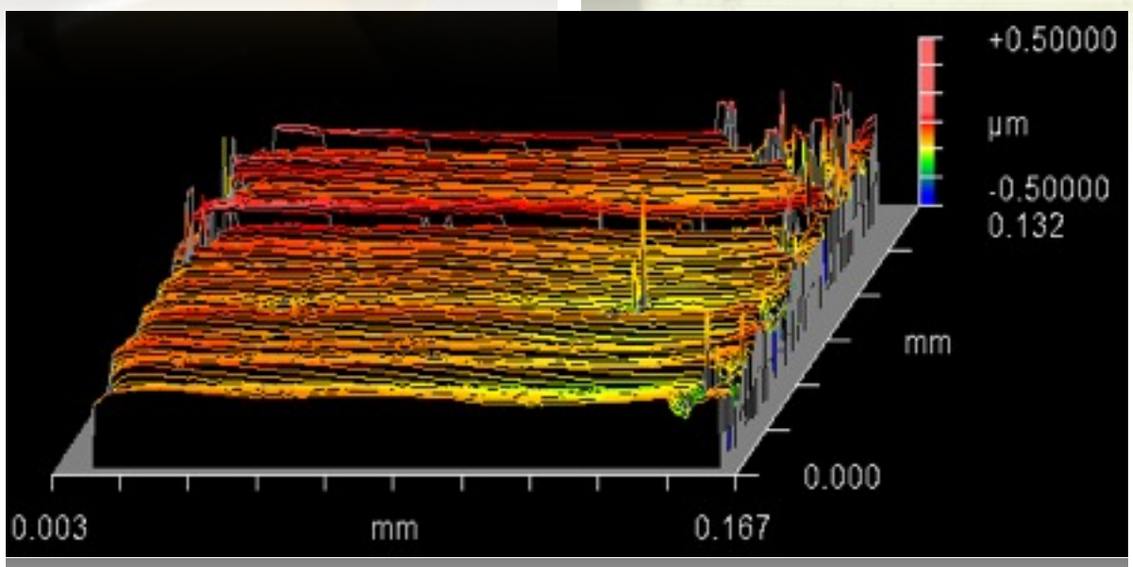
  ~20 nm rms @ Off axis

  ~5 nm rms @ On axis



LIGA-fabricated mirror chip

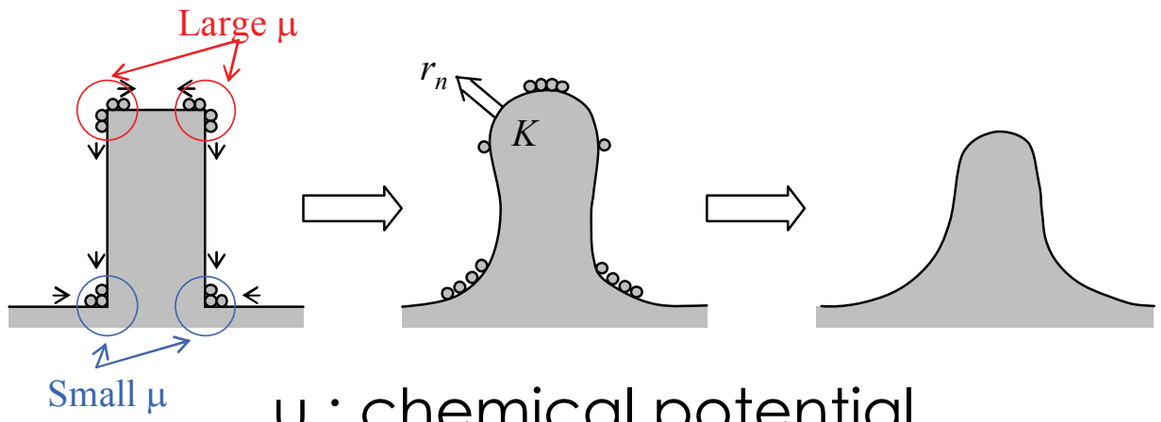


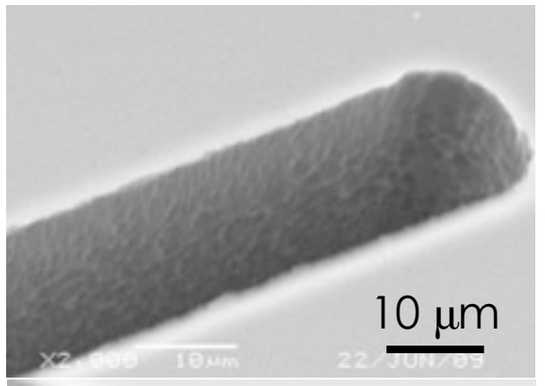


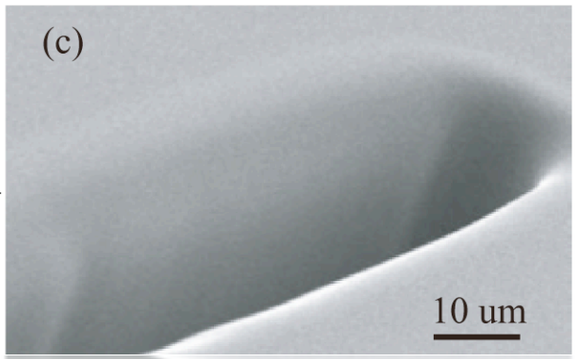
micro pore surface

Step 2 : Finishing side walls

- H_2 annealing for DRIE Si

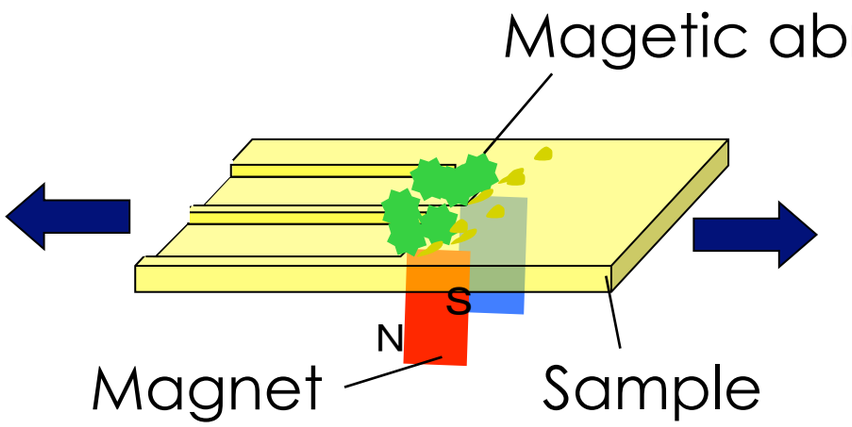




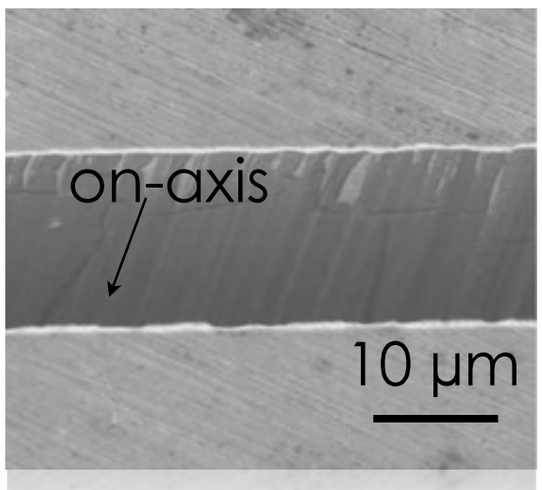


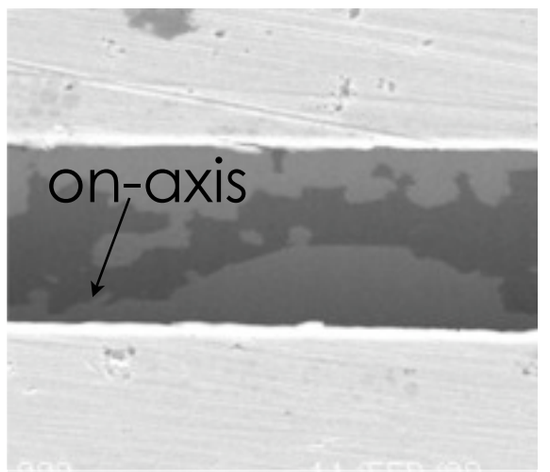
υ : chemical potential

- Magnetic field assisted finishing (MAF) for X-ray LIGA Ni



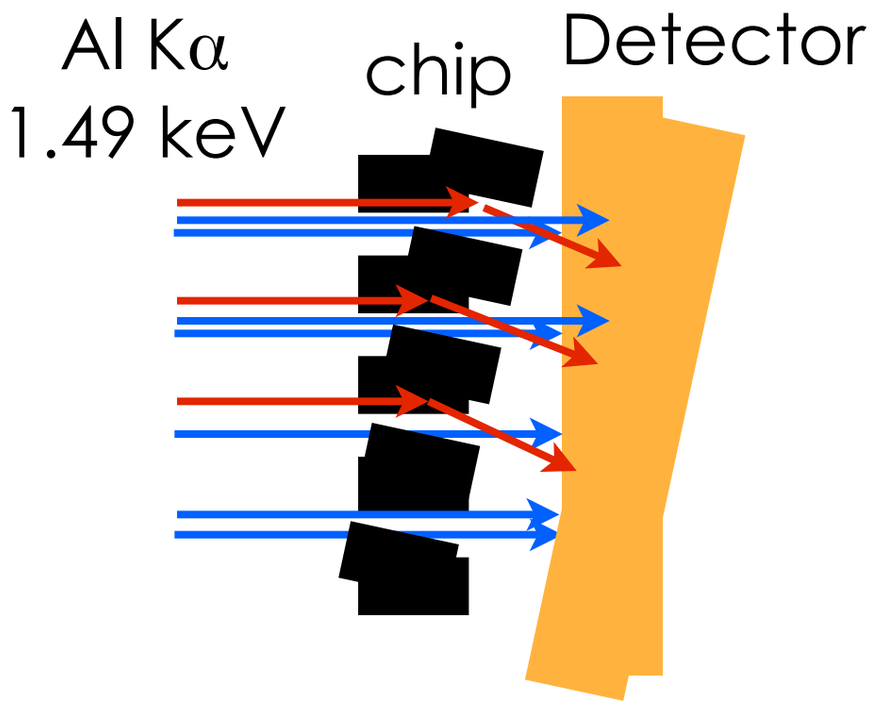
magnetite + water + diamond slurry

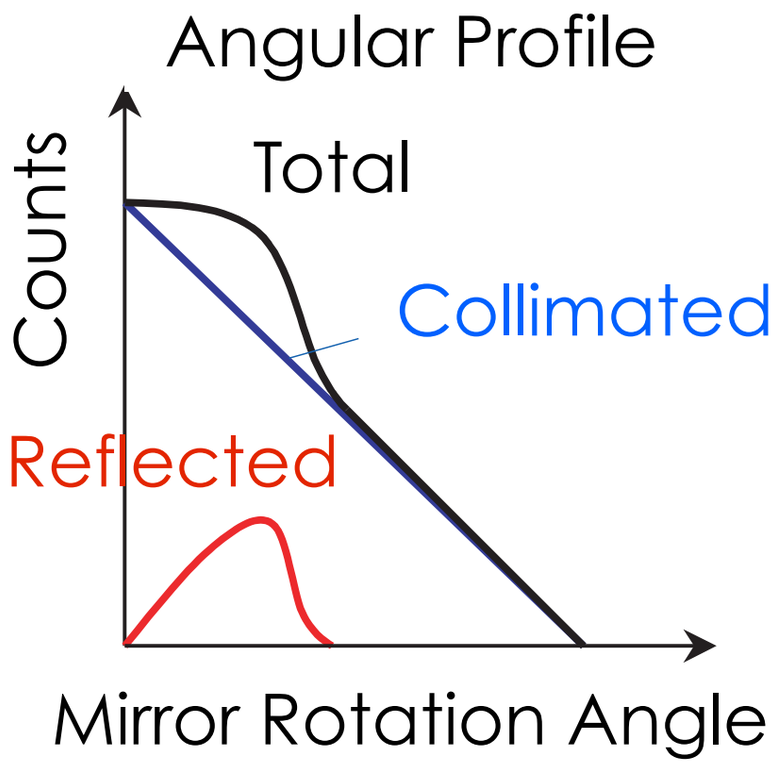




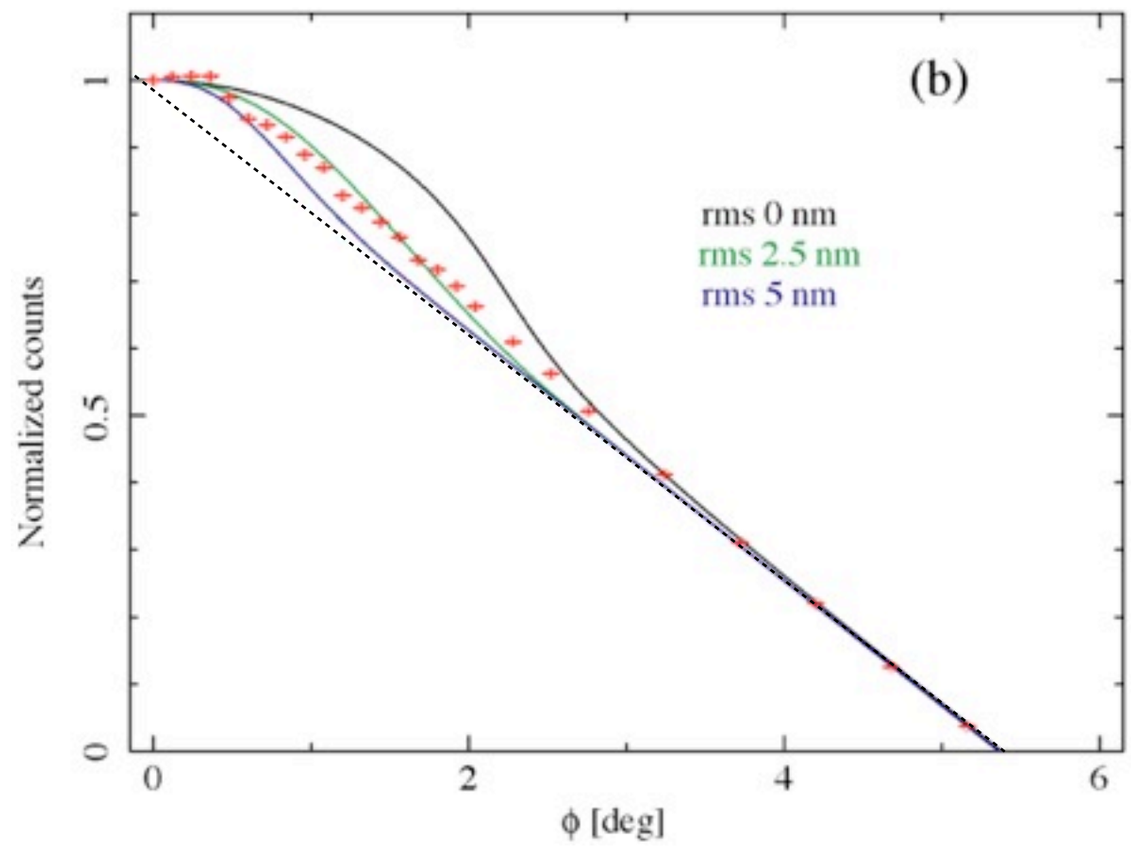
Riveros+09 SPIE

X-ray Reflection Test





LIGA + MAF Ni



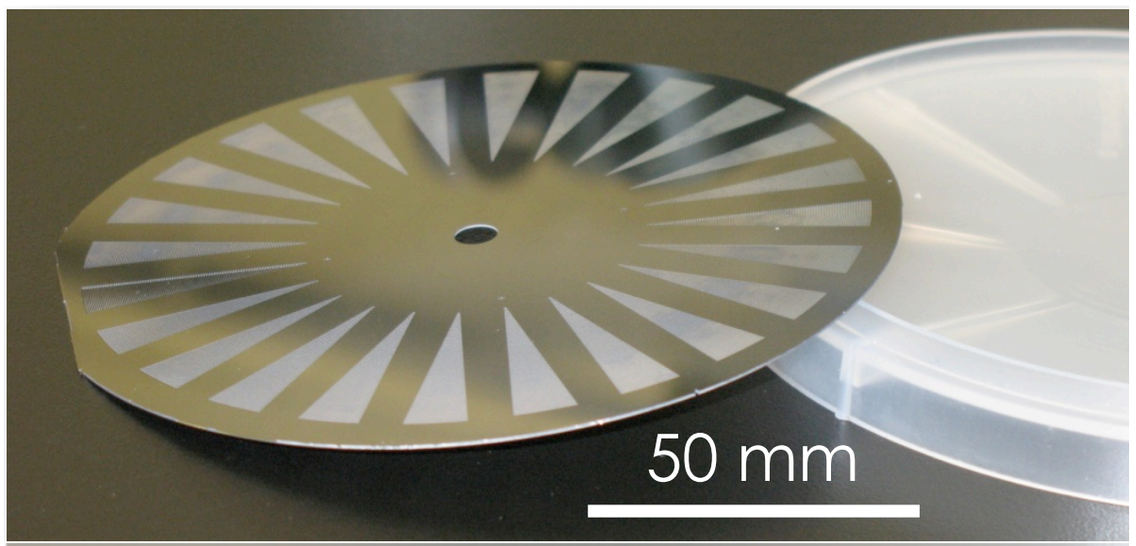
- σ_{rms} = 2.5±0.1 nm for LIGA + MAF Ni
- σ_{rms} = 4.6±0.2 nm for DRIE + H_2 anneal Si

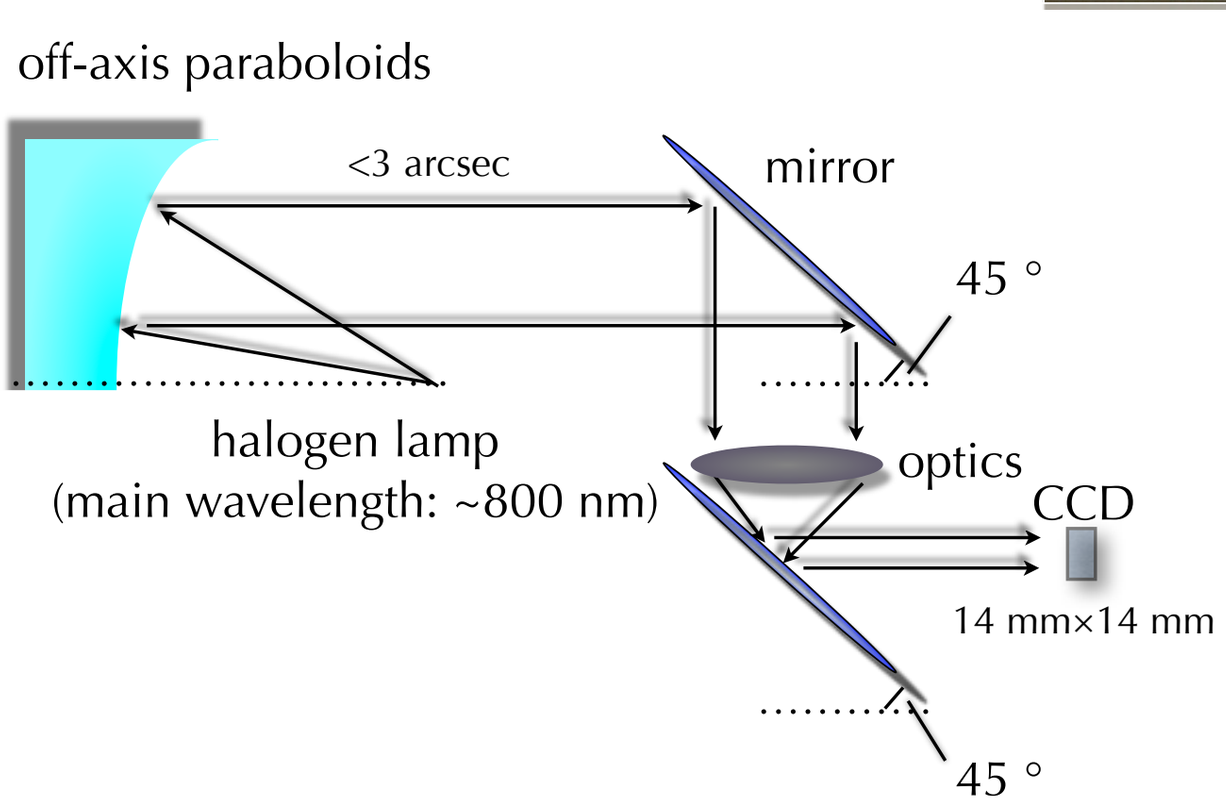
Ezoe+ Microsys. Tech. in press

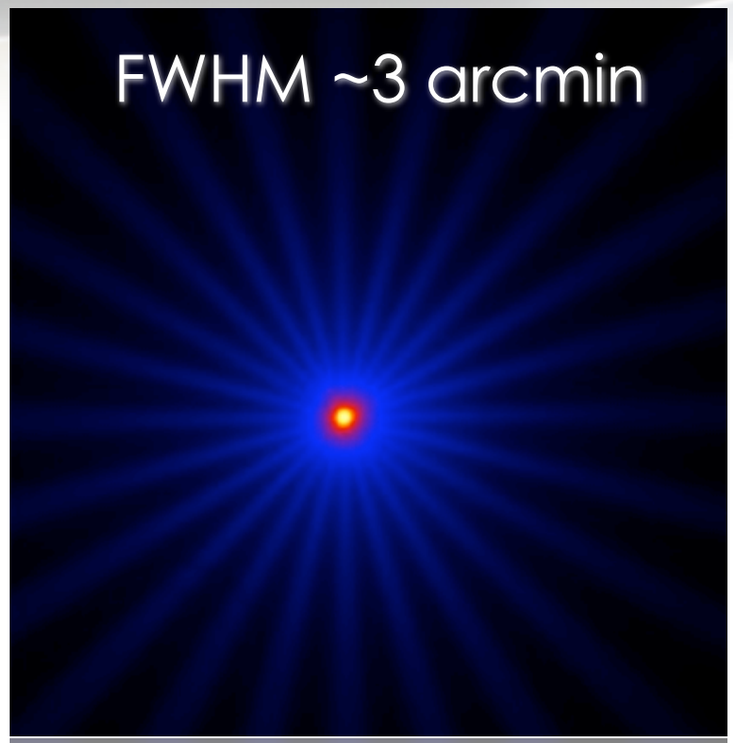
Step 3. Deformation

- Hot plastic deformation
  - Spherical radius : 1 m
  - **No side wall finishing**
- optical imaging
  - form accuracy

Mitsuishi+ IEEE JQE submitted

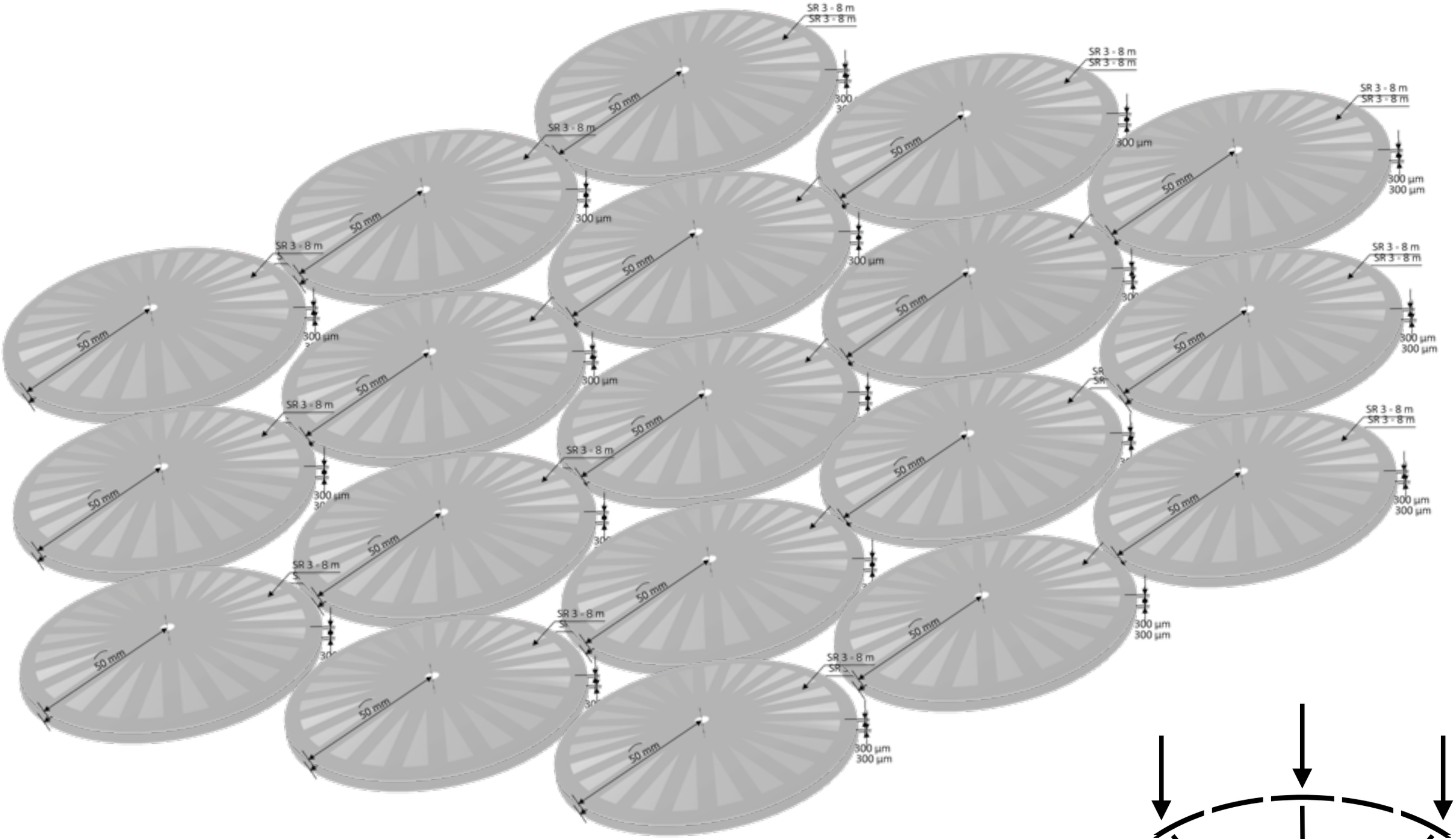


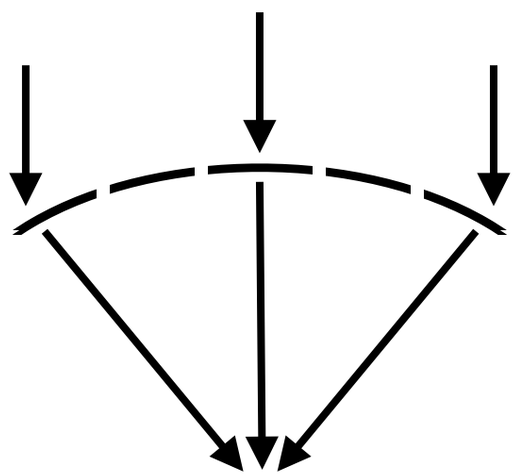




Current development

- Fabrication of single-stage Si & Ni optics
  - New photo masks for high filling factor (Si ✔, Ni)
  - New dies designed for Micro-X and DIOS ✔
  - Improvement on H_2 annealing & MAF
- X-ray Imaging test until this Japanese fiscal year (2010 March)

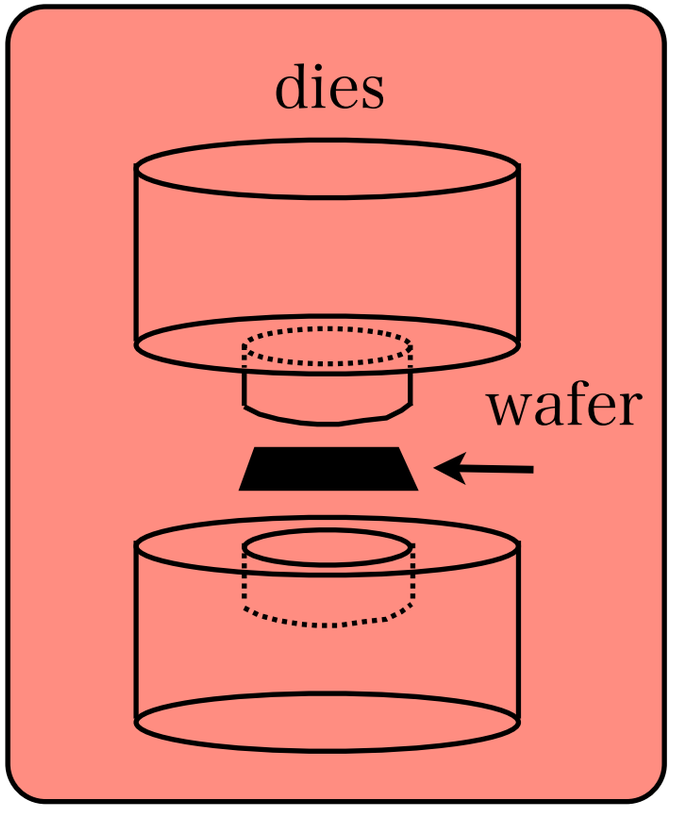

SR 3 - 8 m
50 mm
300 µm



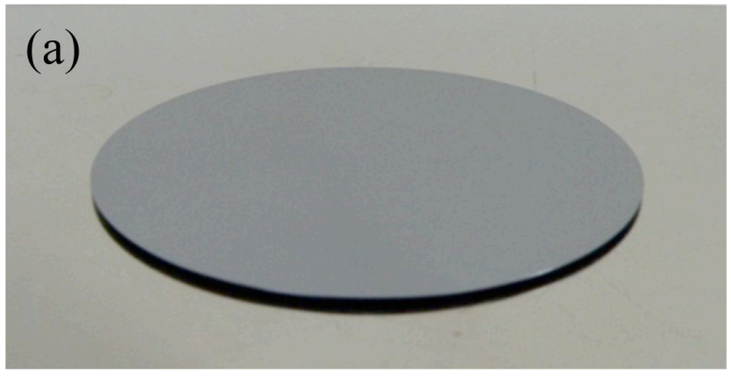
2. Plastically-shaped Si optics

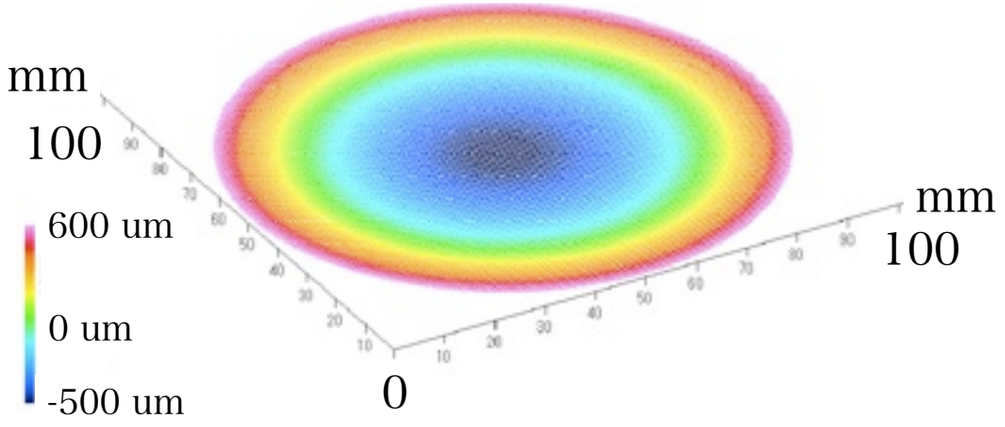
- Si wafer for mirror substrate instead of Al foil
- Hot plastic deformation of Si Nakajima+04 Nature Materials
  - no spring back after shaping
  - applicable for foil optics and SPO

>900 ℃



spherical, R 1 m

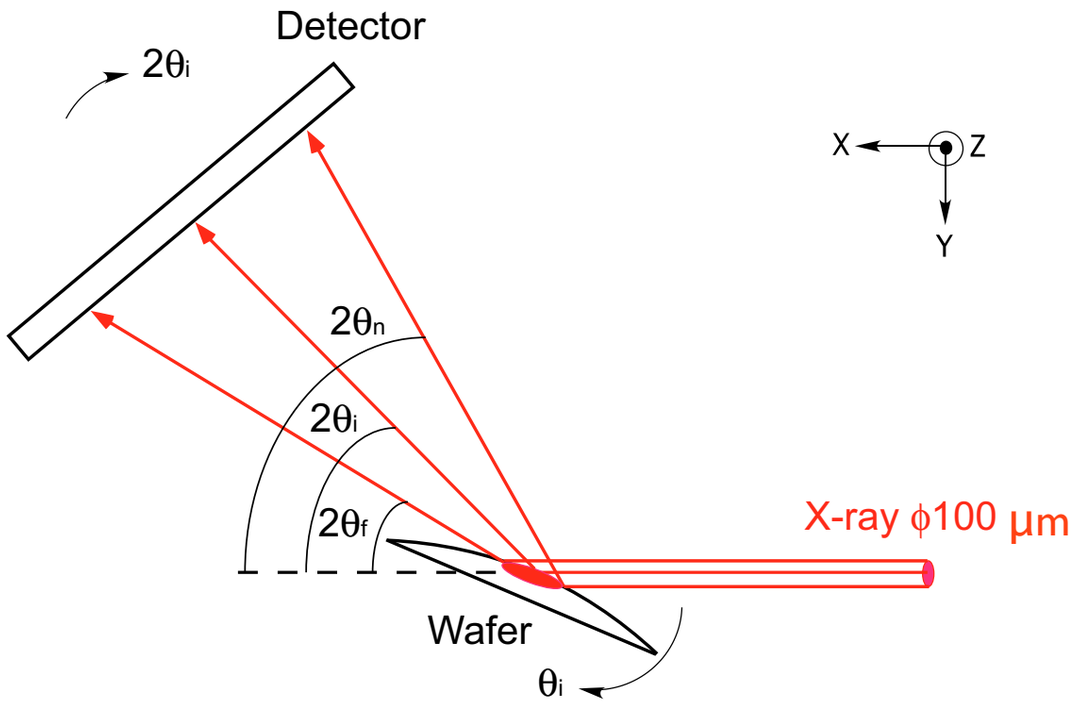


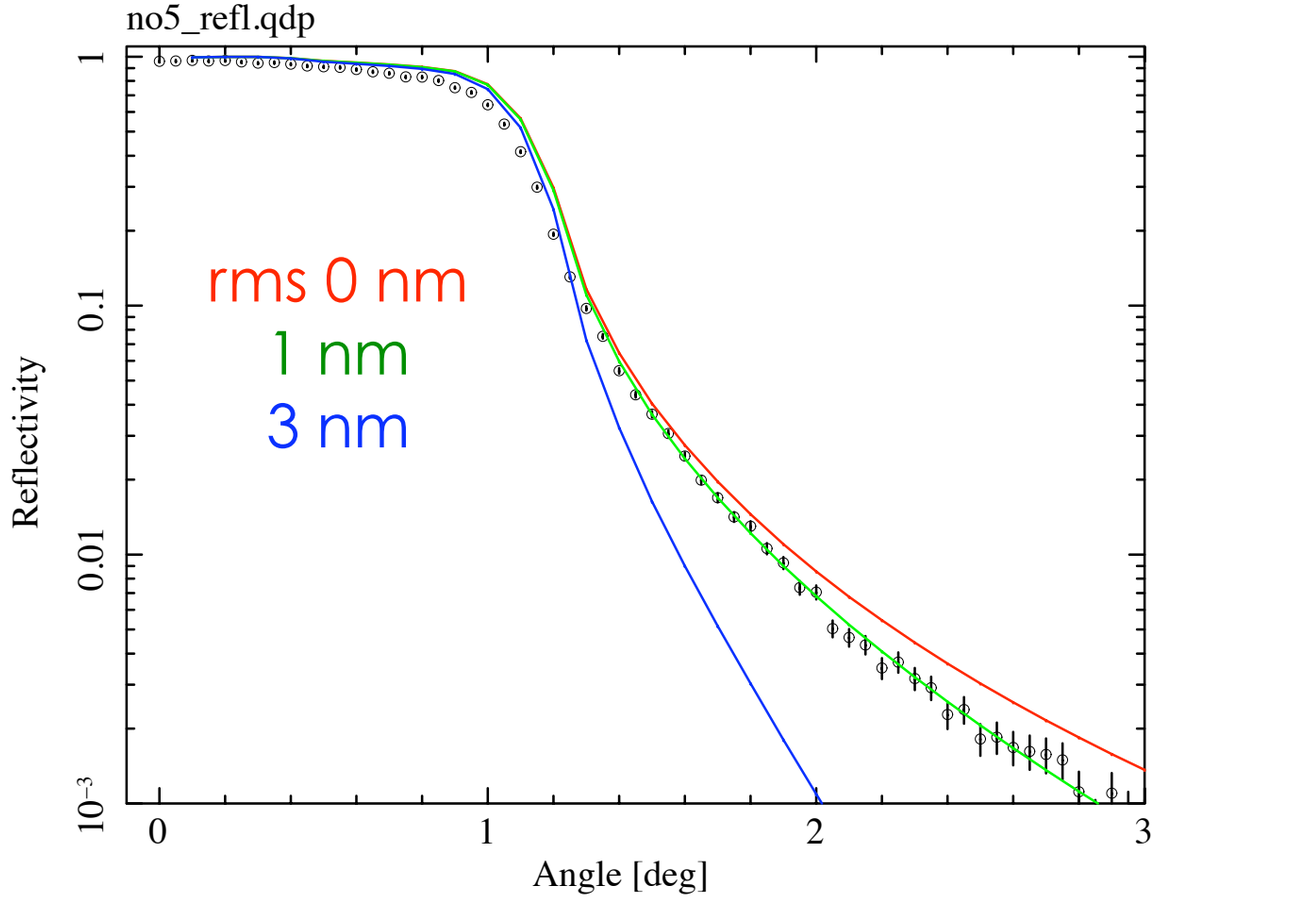


Ezoe+-09 Applied Optics

X-ray Reflection

- X-ray reflectivity @ Al Kα 1.49 keV
  - rms roughness ~ 1 nm
  - no significant change before/after shaping
- Verification of X-ray reflection on shaped Si wafer



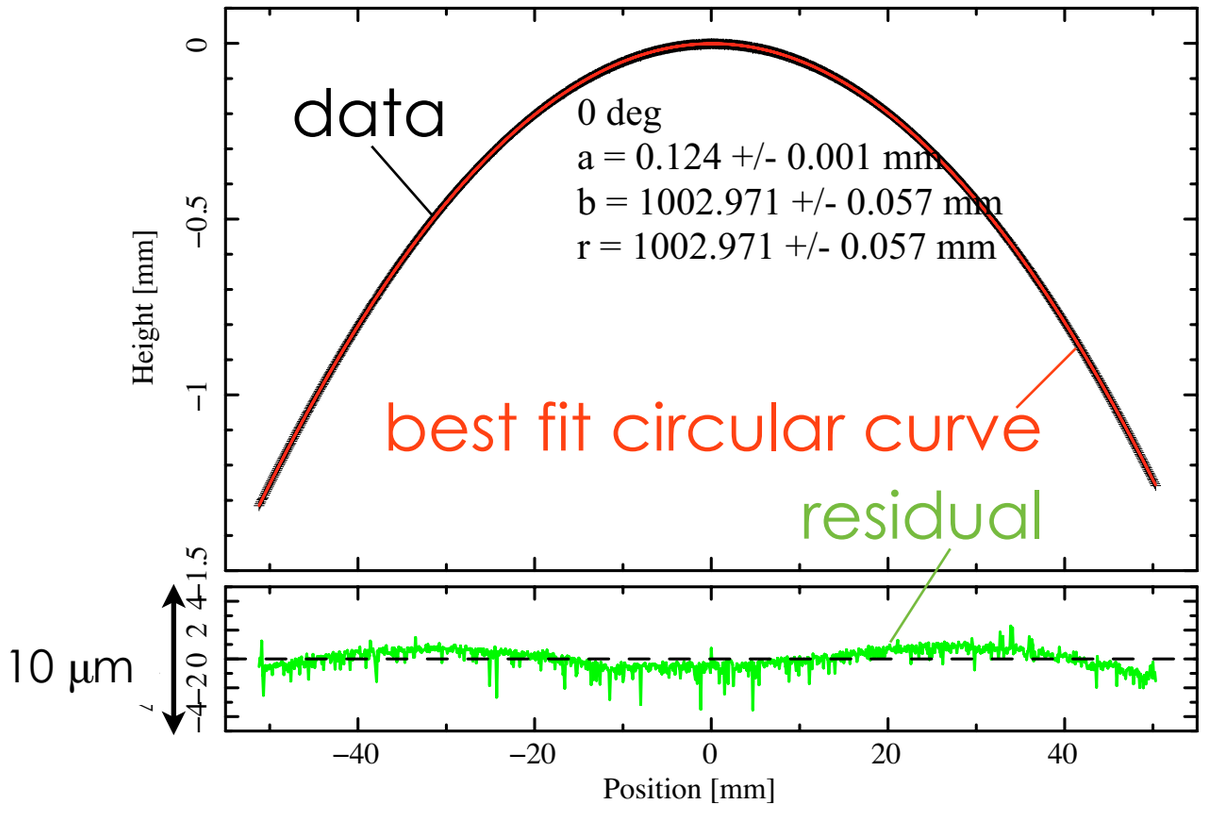


Ezoe+ 09 Applied Optics

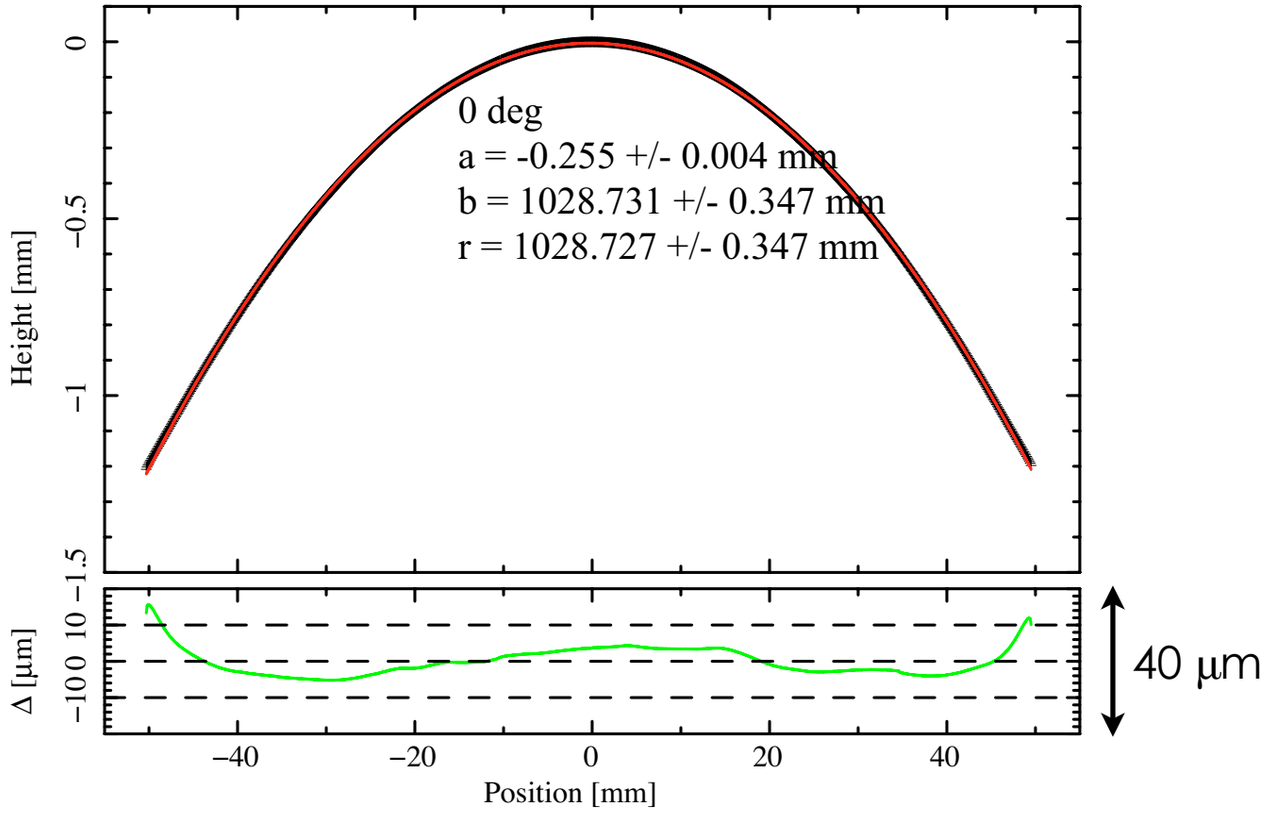
Form Accuracy

- Wafer shape was NOT good
  - Die : R ~ 1003 mm, residual ~2 μm peak to valley
  - Wafer : R ~ 1030 mm, residual ~20 μm

deformation die



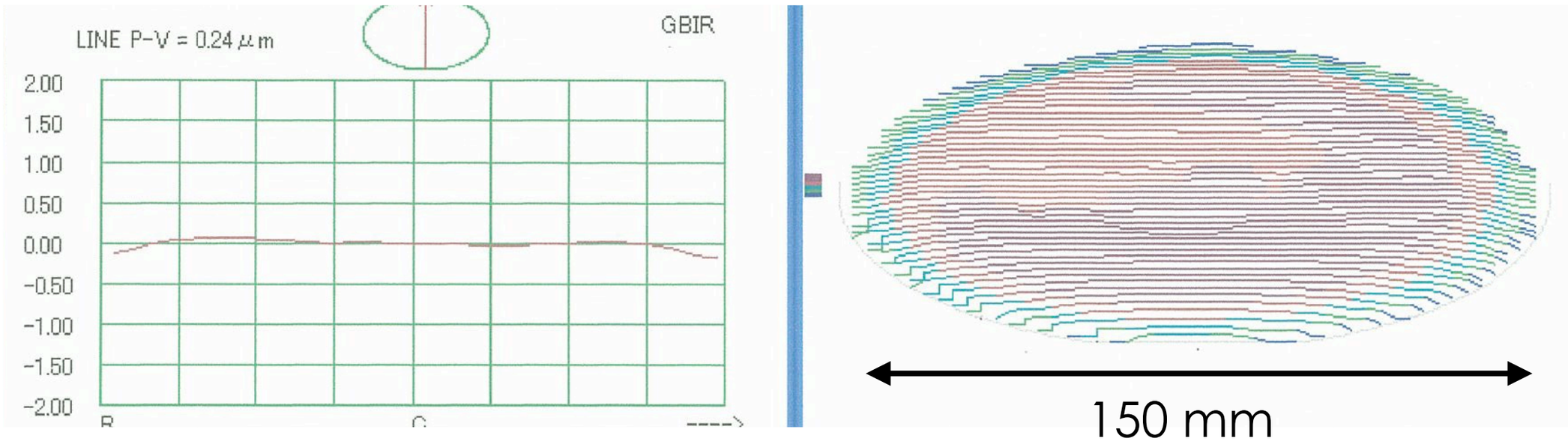
wafer



Ezoe+ 09 Applied Optics

Current development

- Smooth & flat wafers
  - TTV (total thickness variation) on the order of 0.1 μm ✔
  - micro roughness on the order of 0.1 nm ✔
- Deformation process
  - New conical deformation dies ✔
- X-ray imaging test of conically shaped wafer



Acknowledgment

I. Mitsuishi, M. Koshiishi, Dr. M. Mita,
Prof. M.Ishida, Prof. K. Mitsuda

U. Takagi, K. Ishizu, T. Moriyama, T. Hayashi, T. Sato, T. Shonome, Prof. T. Ohashi

Dr. K. Fumiki, Dr. M. Horade, Prof. S. Sugiyama

Dr. K. Morishita, Prof. K. Nakajima,
S. Fujihira, Prof. Y. Kanamori

R. Riveros, T. Boggs, Prof. H. Yamaguchi

T. Takano, Dr. R. Maeda