Metal-coated MEMS X-ray optics using atomic layer deposition

D. Ishi, Y. Ezoe, M. Numazawa, A. Fukushima, R. Otsubo,
H. Suzuki, T. Yuasa, S. Sakuda, T. Uchino (Tokyo Metropolitan Univ.),
K. Ishikawa, K. Mitsuda (ISAS/JAXA)

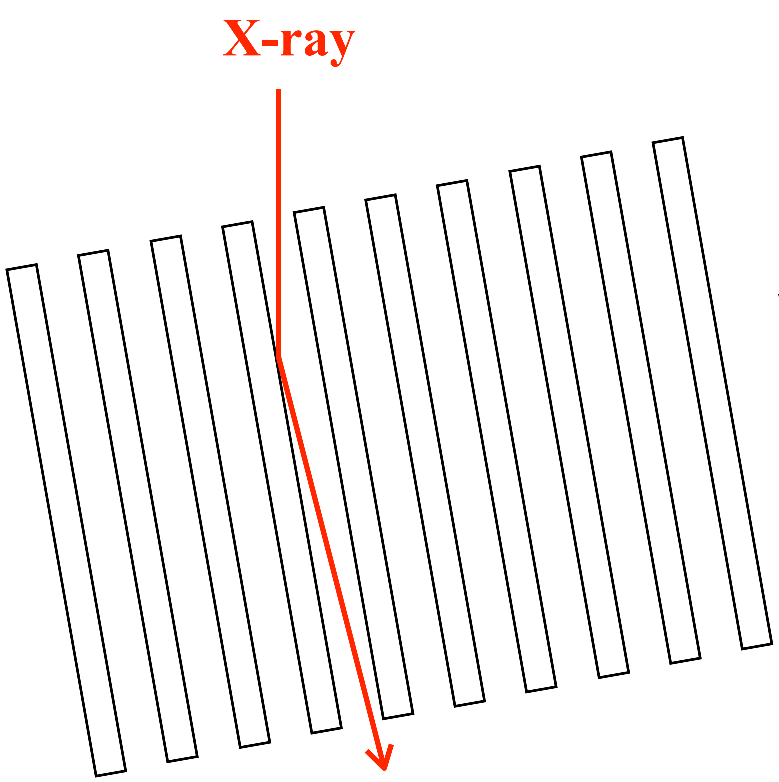
AXRO 2019, Prague, 5 December 2019

Outline

- **Introduction**
  - **MEMS X-ray optics & Atomic Layer Deposition (ALD)**
- **Our past developments & issues : "Surface roughness"**
  - **Thermal & Plasma Pt ALD**
- **Our future prospects : "Soft X-ray reflectivity"**
  - **Co- & Ni-ALD**
  - **SiC/Pt & BN/Pt**
- **Summary**

Introduction

- **Next-generation X-ray telescopes : high-resolution & light-weight**
  - **Micro pore optics : side walls of micro pores for X-ray mirrors**

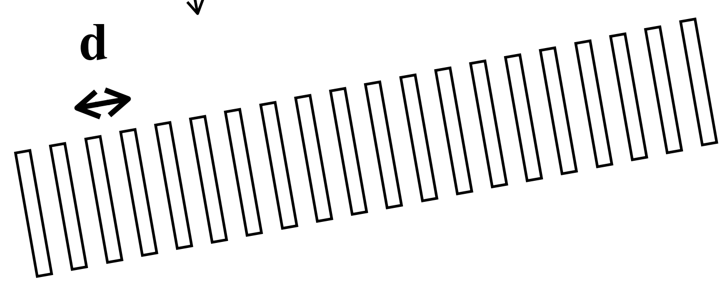


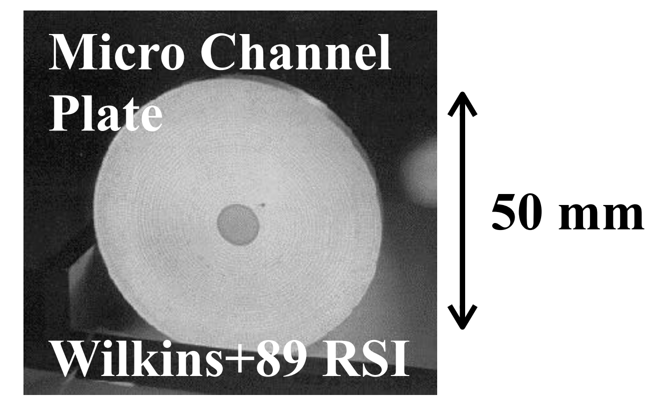
Mass per one mirror ∝ A^{-3}

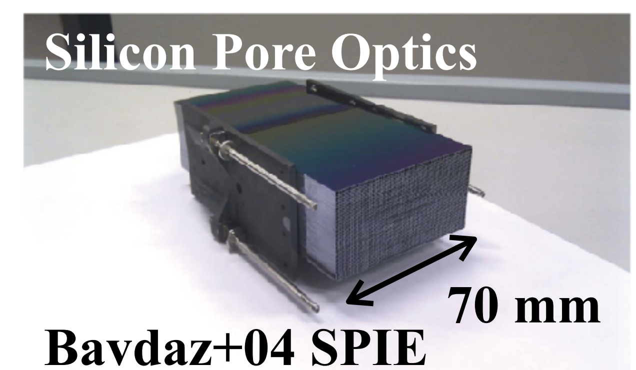
Mirror number ∝ A^2

Telescope weight ∝ $A^{-3+2} = A^{-1}$

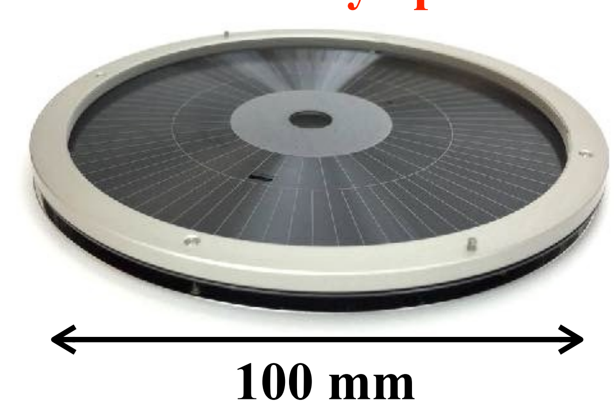
×1/A







MEMS X-ray optics



Ezoe+05 SPIE
Ezoe+12 OL

  - **X-ray diffraction : limits on size reduction**

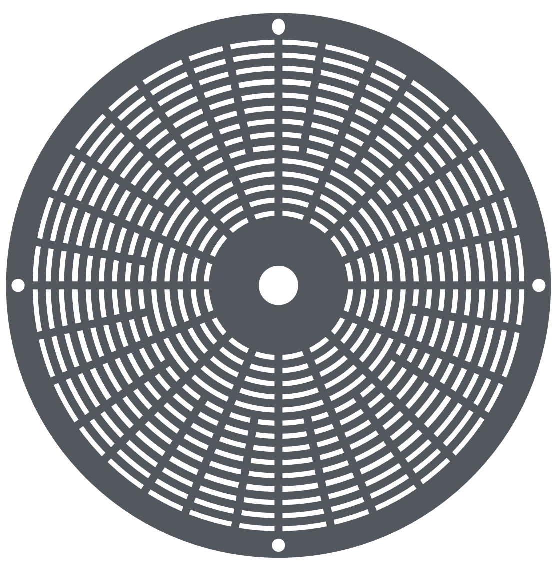
$$\Delta\theta \sim \frac{d}{\lambda} \sim 13'' \left(\frac{d}{20\ \mu\mathrm{m}}\right) \left(\frac{E}{1\ \mathrm{keV}}\right)$$

*Micro-Electro Mechanical Systems

Ezoe+10 Microsys. Tech.
Mitsuishi+12 Sens. Act. A
Ogawa+13 Appl. Opt.
Ishikawa+17 Microsys. Tech.
Takeuchi+18 Appl. Opt, etc

MEMS* X-ray optics

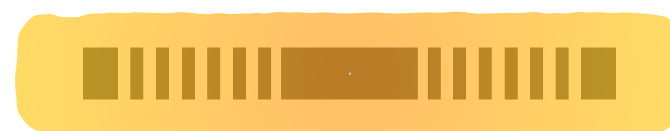
1. Deep Reactive Ion Etching (DRIE)
- fabricate micropores



Pore width 20 µm

4-12 inch & 300-500 um-thick
Si (111) wafer

2. Hydrogen annealing
- smooth sidewalls

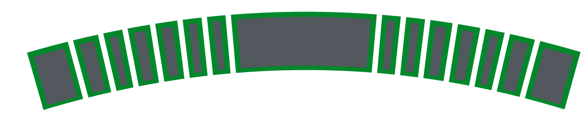


Micro-roughness
<1 nm rms

3. Plastically deforming
- focus X-rays

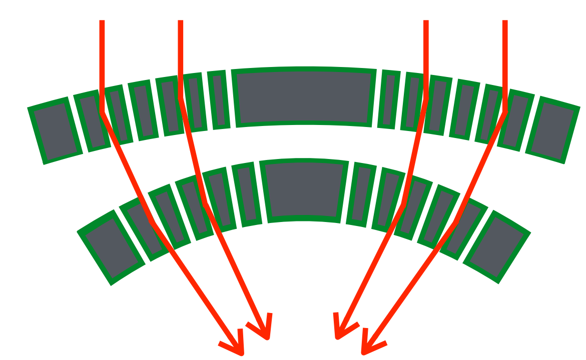
Curvature radius
1000 & 333 mm

4. Noble-metal coating
- enhance reflectivity



High-Z material
Ir & Pt

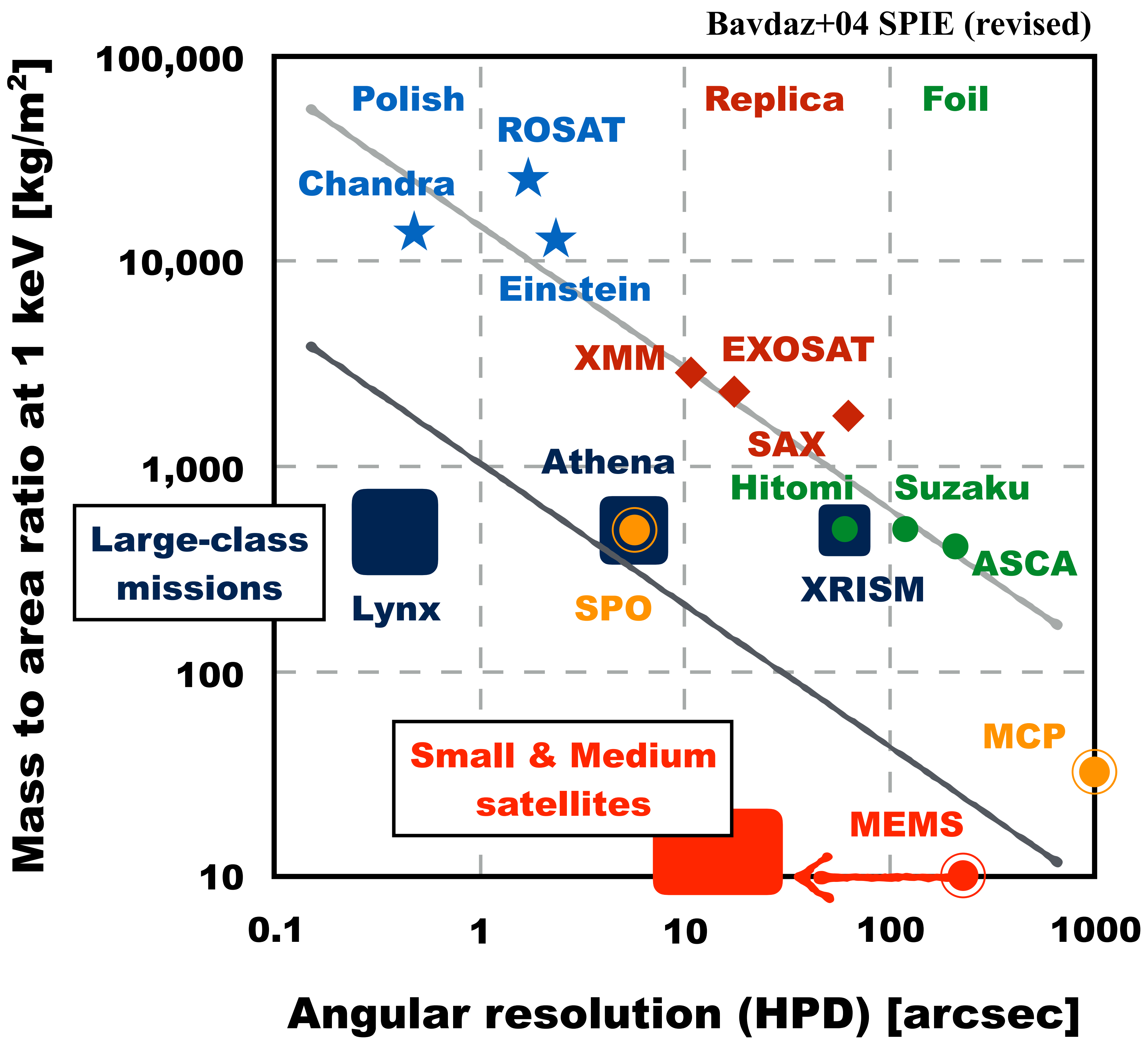
5. Precise stacking
- form Wolter-I optics



Focal length
250 mm

- In-house fab. : low-cost
- Telescope weight : ~5 g = ultra light-weight
- Angular res. : ~13 arcsec = X-ray diffraction at 1 keV

Objectives



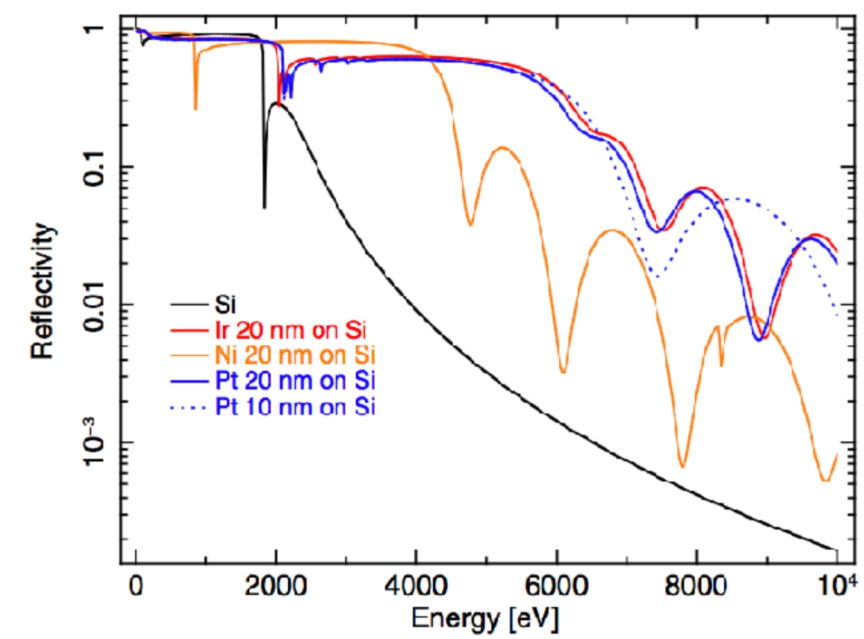
Bavdaz+04 SPIE (revised)
Polish
ROSAT
Replica
Foil
Chandra
Einstein
XMM
EXOSAT
SAX
Athena
Hitomi
Suzaku
ASCA
Large-class missions
Lynx
SPO
XRISM
MCP
Small & Medium satellites
MEMS
100,000
10,000
1,000
100
10
0.1
1
10
100
1000
Mass to area ratio at 1 keV [kg/m²]
Angular resolution (HPD) [arcsec]

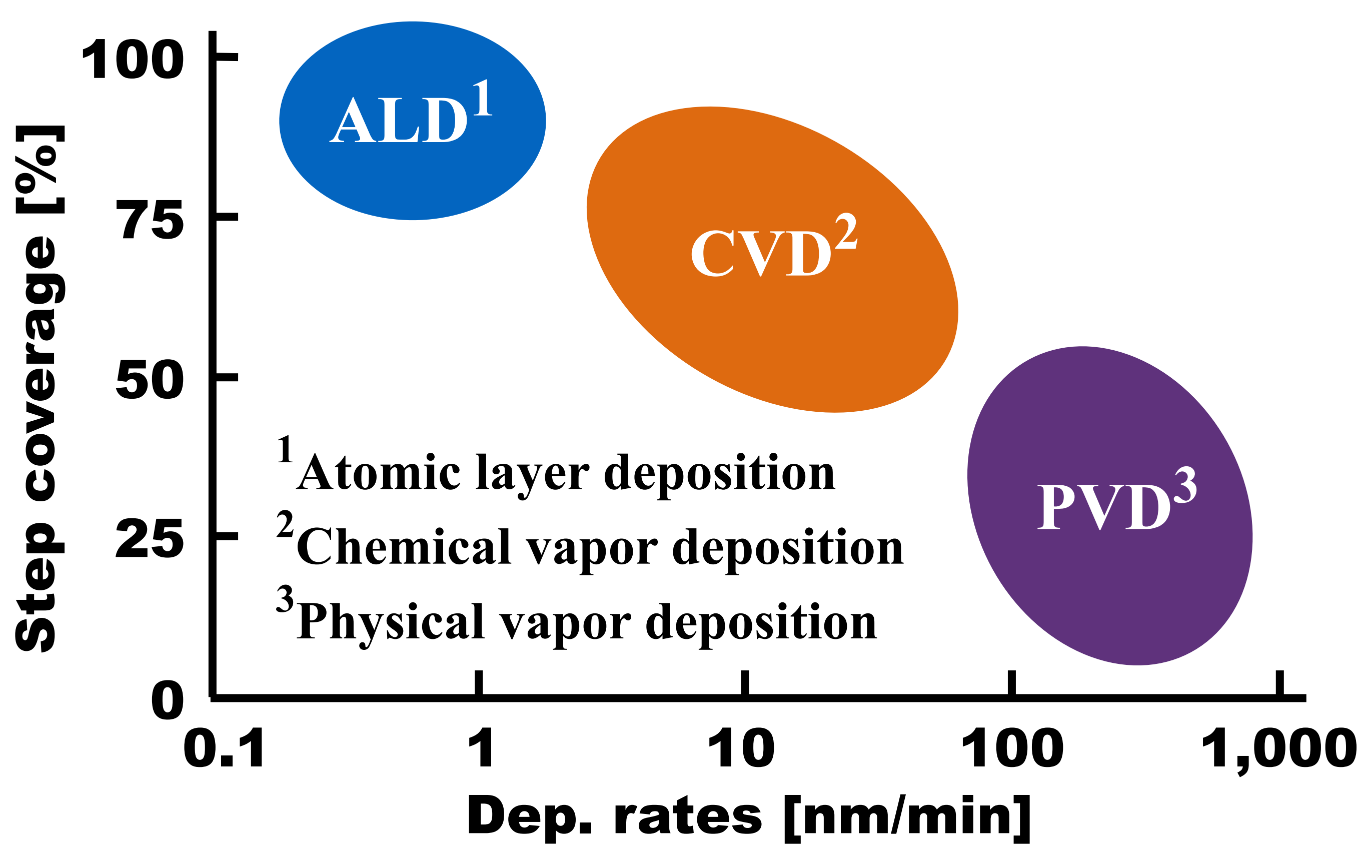
Toward future satellites

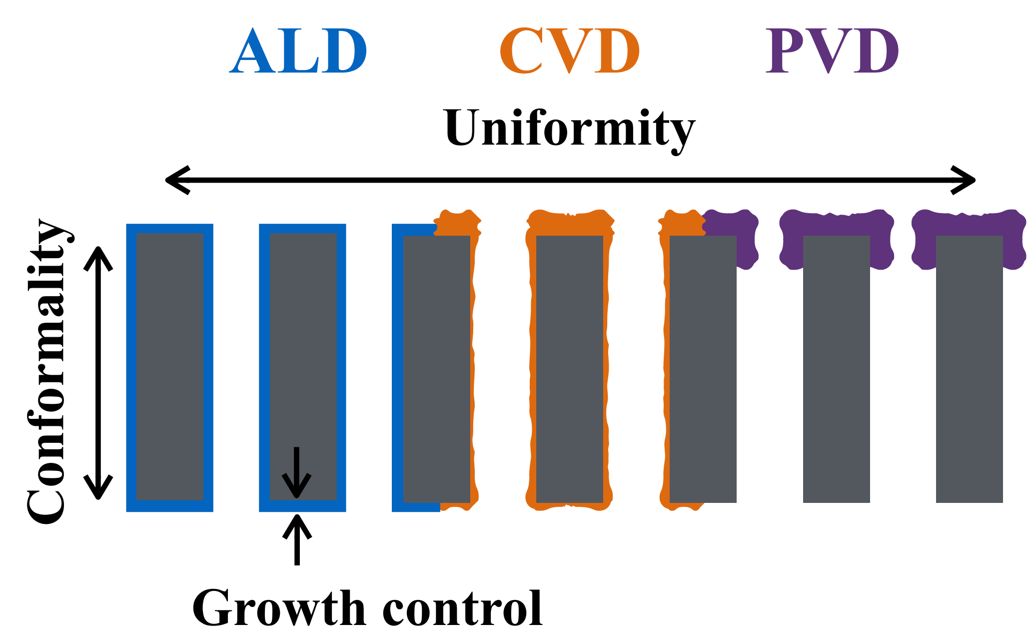
- Key techniques : **high-Z metallic coatings on high-aspect micro pores**

- Stricter coating requirements :
  - Precise growth & thickness control
  - High conformality & Step coverage
  - Good uniformity on large-area substrates

Incident angle at 1 deg





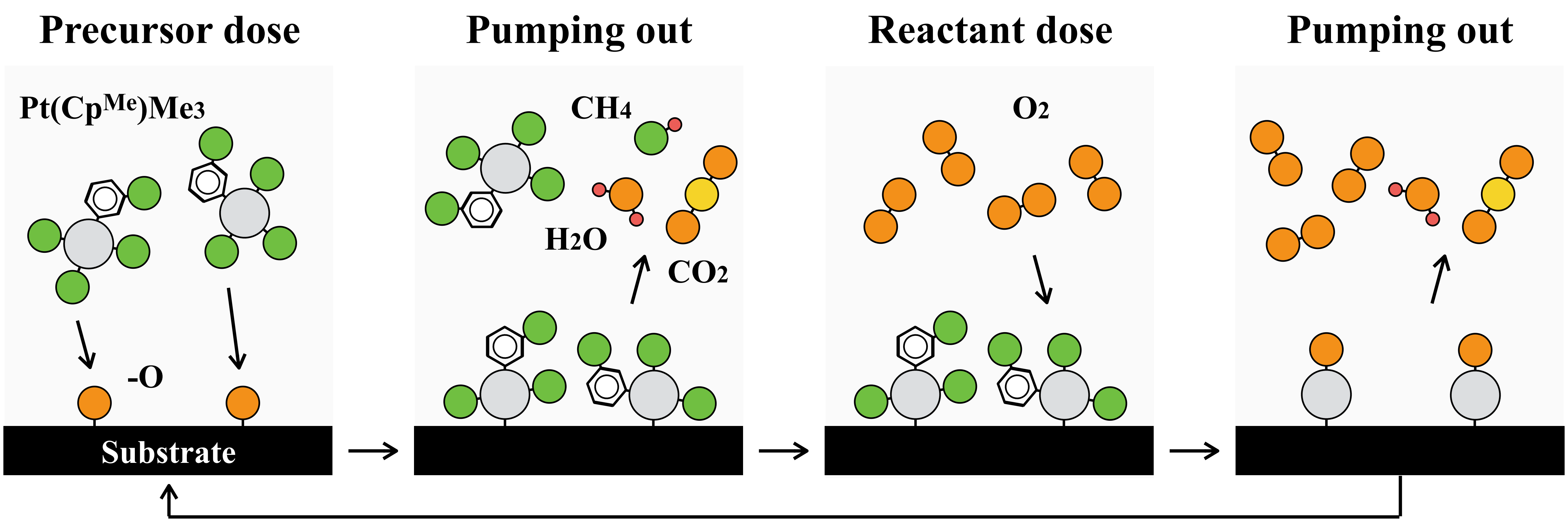


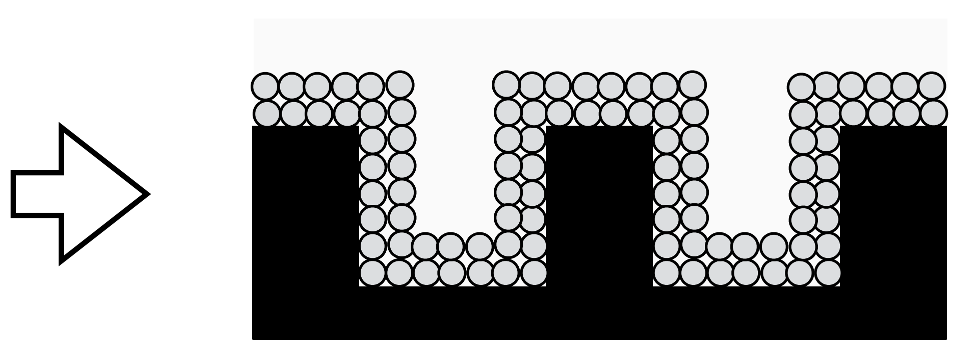
Atomic Layer Deposition (ALD)

- **Self-limiting & Sequential surface reactions :**

$$2(\mathrm{MeCp})\mathrm{PtMe_3} + 3\mathrm{O(ads.)} \rightarrow 2(\mathrm{MeCp})\mathrm{PtMe_2} + \mathrm{CH_4} + \mathrm{CO_2} + \mathrm{H_2O}, \quad \textbf{(1)}$$

$$2(\mathrm{MeCp})\mathrm{PtMe_2} + 24\mathrm{O_2} \rightarrow 2\mathrm{Pt} + 3\mathrm{O_2} + 16\mathrm{CO_2} + 13\mathrm{H_2O}. \quad \textbf{(2)}$$



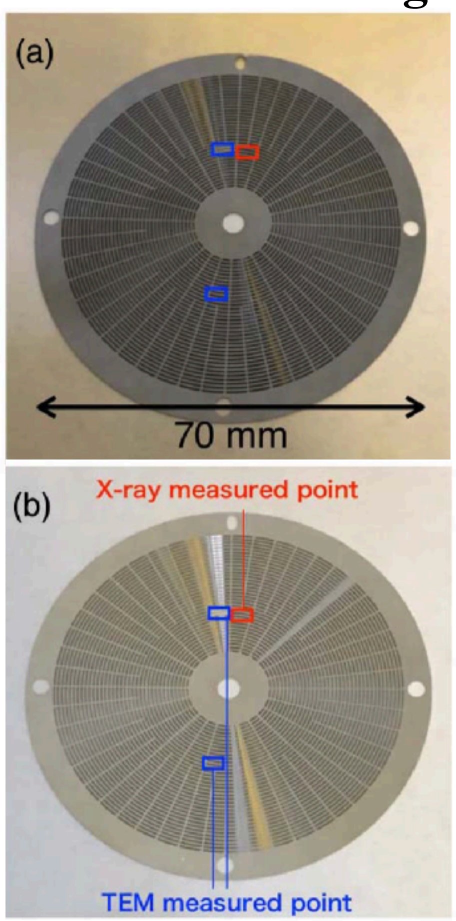


- **The best coating technique for micro pore optics !!**

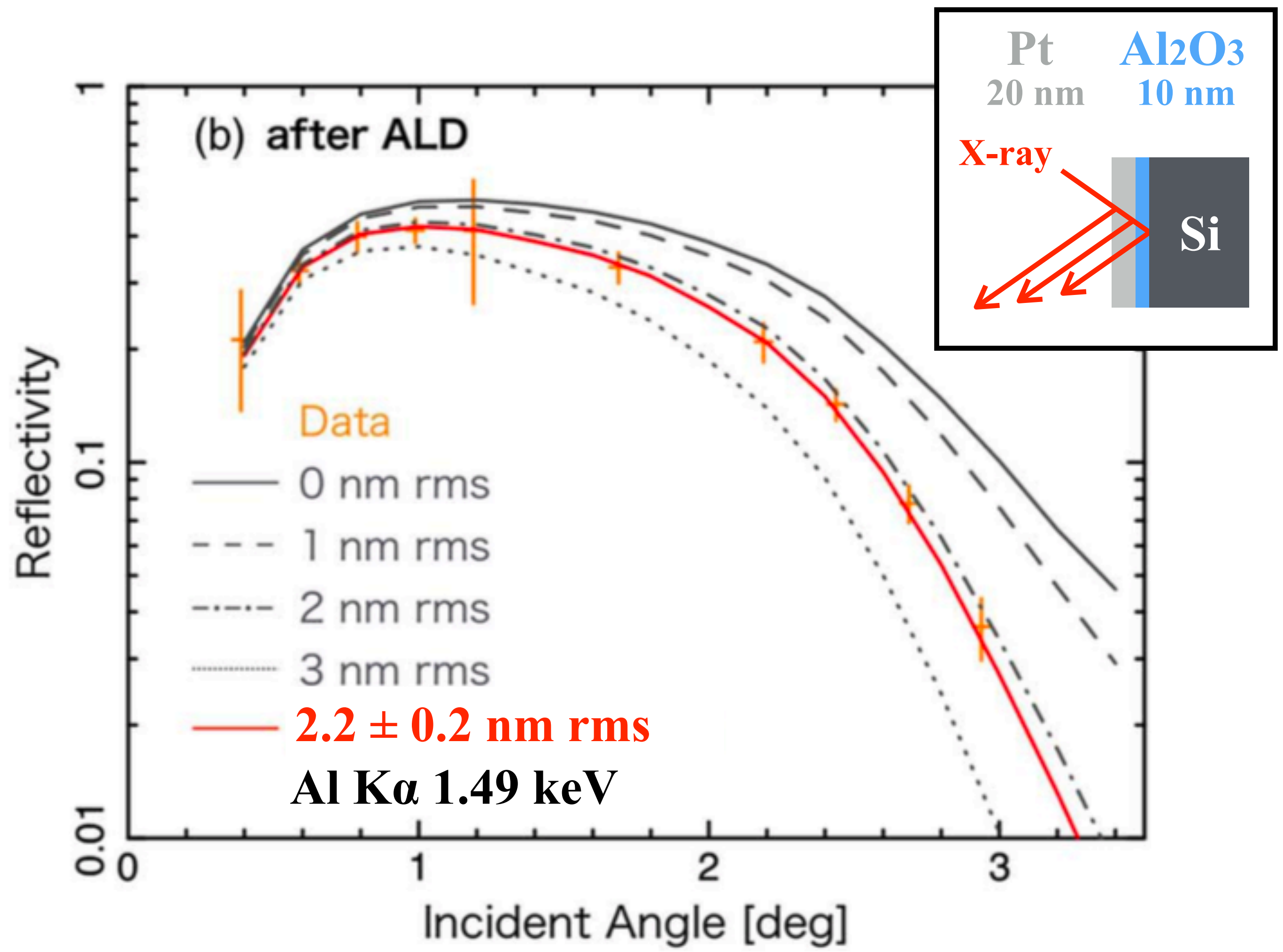
Our past developments & issues

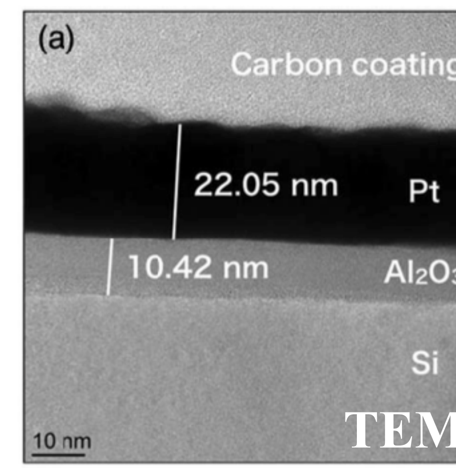
- **First ALD demonstrations for micro pore optics :**
  - **Ir (Ogawa+13 Appl. Opt.) & Pt (Takeuchi+18 Appl. Opt. Editor's Pick)**

DRIE + annealing

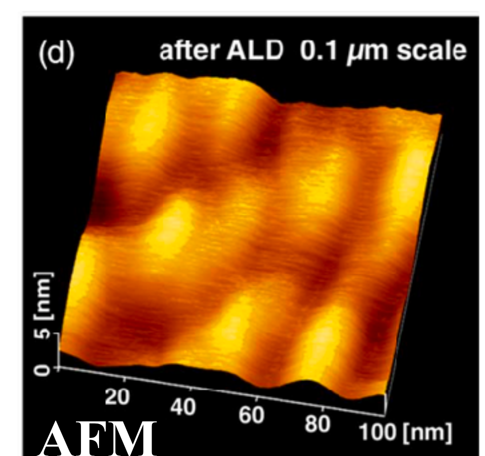


Thermal Pt ALD





Adhesion layer

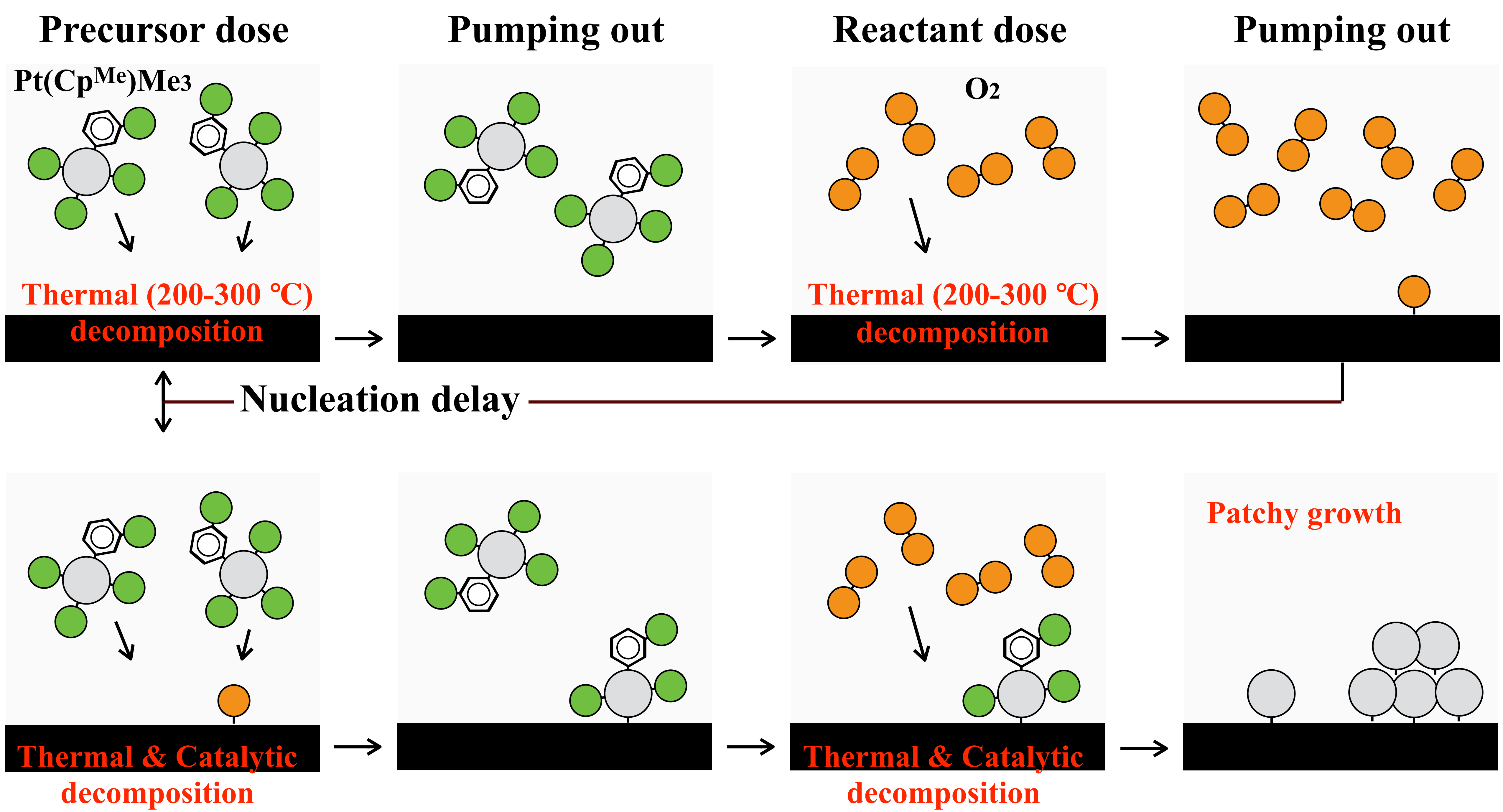


- **Large surface roughness of Pt : patchy growth = nucleation delay ?**

(Before ALD : 1.6 ± 0.2 nm rms / After ALD : 2.2 ± 0.2 nm rms / Requirement : <2 nm rms @ <2 keV)

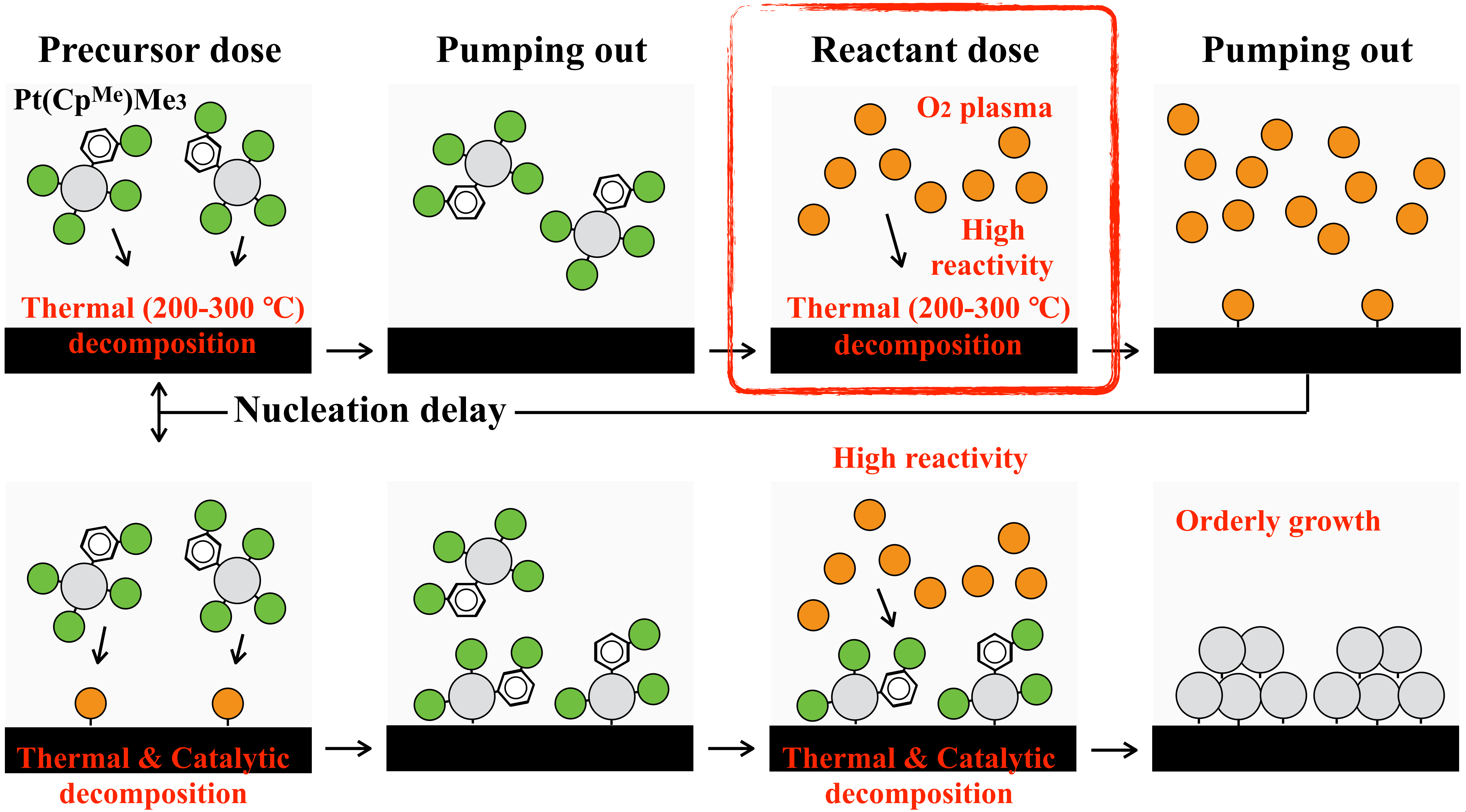
Nucleation delay @ Thermal Pt ALD

- Early stages of ALD cycles : poor nucleation



Nucleation delay @ Plasma Pt ALD

- Early stages of ALD cycles : rich nucleation



Ishi+ in prep.

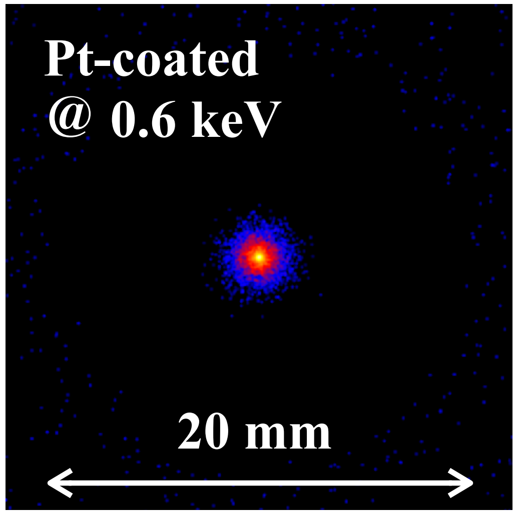
Sample fabrication

- Sample optic : DRIE + annealing

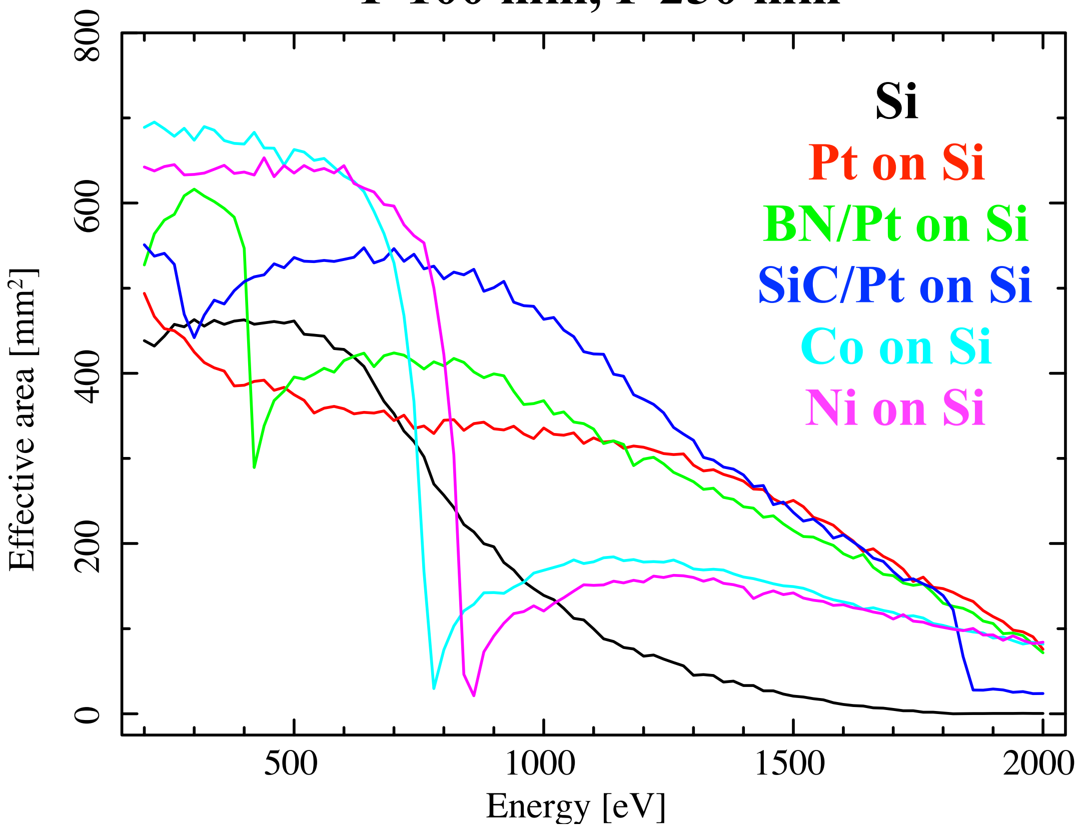
- Successful for Plasma Pt ALD & Smaller Pt islands !!

Our future prospects

- Enhancement of soft X-ray reflectivity :
  - Co- & Ni-ALD
    - Improvement on surface roughness by optimizing coating parameters (e.g., precursors & reactants)
  - SiC/Pt & BN/Pt
    - Improvement on film qualities by changing adhesion layers (e.g., Al_2O_3 & SiO_2)



MEMS Wolter-I simulations
Φ 100 mm, F 250 mm



Summary

- **We have been developing "MEMS X-ray optics"**
  for "small & medium satellites"

- **Our coating techniques : "Atomic Layer Deposition"**
  - **First ALD demonstrations : Ir- & Pt-coated micro pore optics**
    (Ogawa+13 Appl. Opt. & Takeuchi+18 Appl. Opt. Editor's pick)
  - **Better surface roughness : "Plasma Pt ALD"**
    (Ishi+ in prep.)
    - **Further improvement by long-term annealing & post-annealing**
  - **Enhancement of soft X-ray reflectivity : Co, Ni, SiC/Pt, BN/Pt, …**
    - **Improvement on surface roughness & film qualities**

- **Thank you for your attention !!**