

# Deformation of particle-strengthened metal-oxide nanolaminates on polymer

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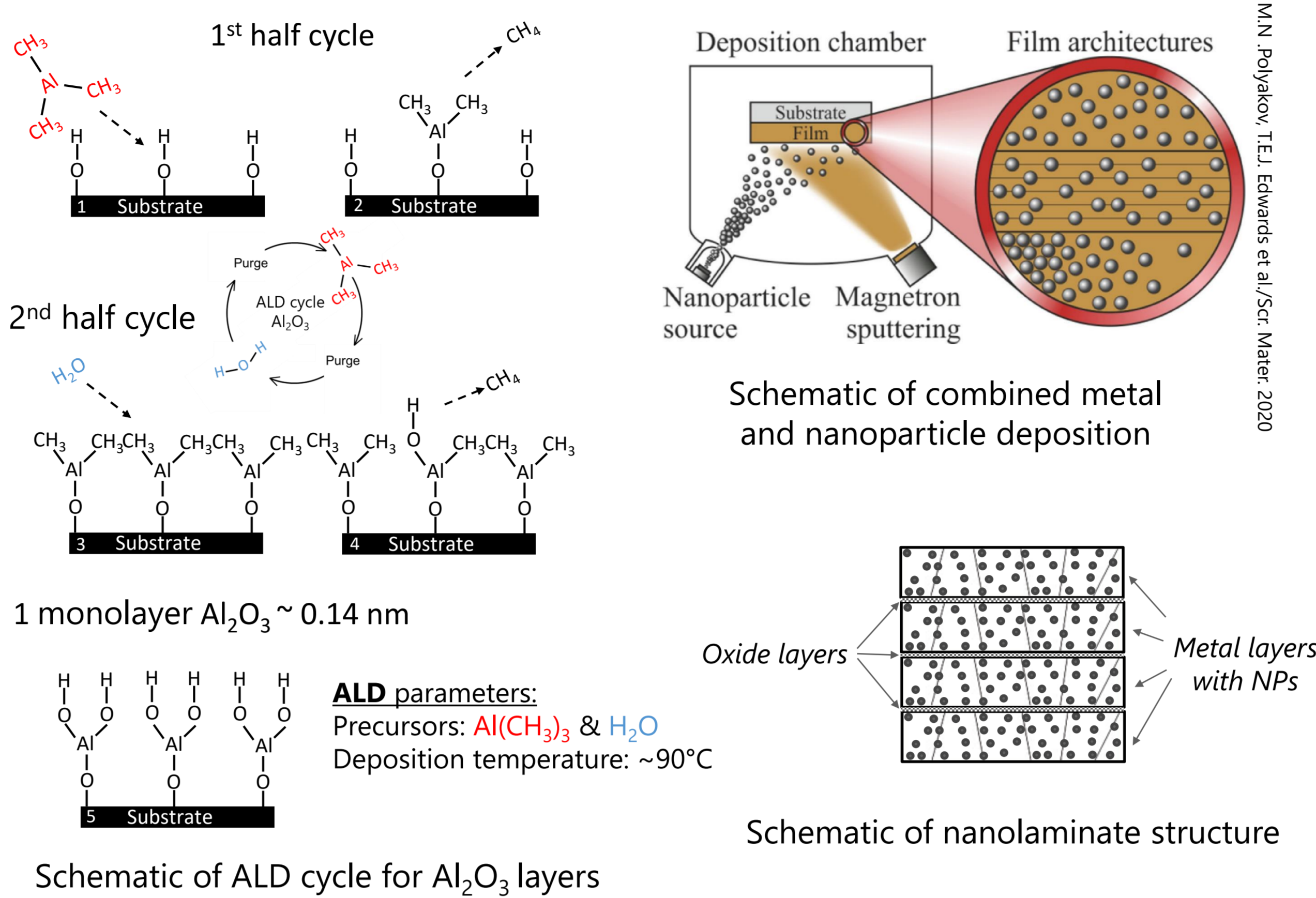
**Abstract:** A unique deposition setup combining atomic layer (ALD), physical vapour (PVD, magnetron sputtering) and nanoparticle (NP) deposition was used to fabricate a series of thin film multilayer structures of particle-strengthened metal (Al, Au, PVD + W NPs) and oxide layers (Al<sub>2</sub>O<sub>3</sub>, ALD) on flexible polymer substrates without breaking vacuum. The multilayers were strained in uniaxial tension to investigate their deformation behavior. Film stresses in the metal layers, measured in situ with X-ray diffraction, in situ resistance measurements and post-mortem SEM analysis of the thin film surfaces reveal strengthening, and changes in the fragmentation behavior as a function of NP content, metal and oxide layer thickness.

## Motivation

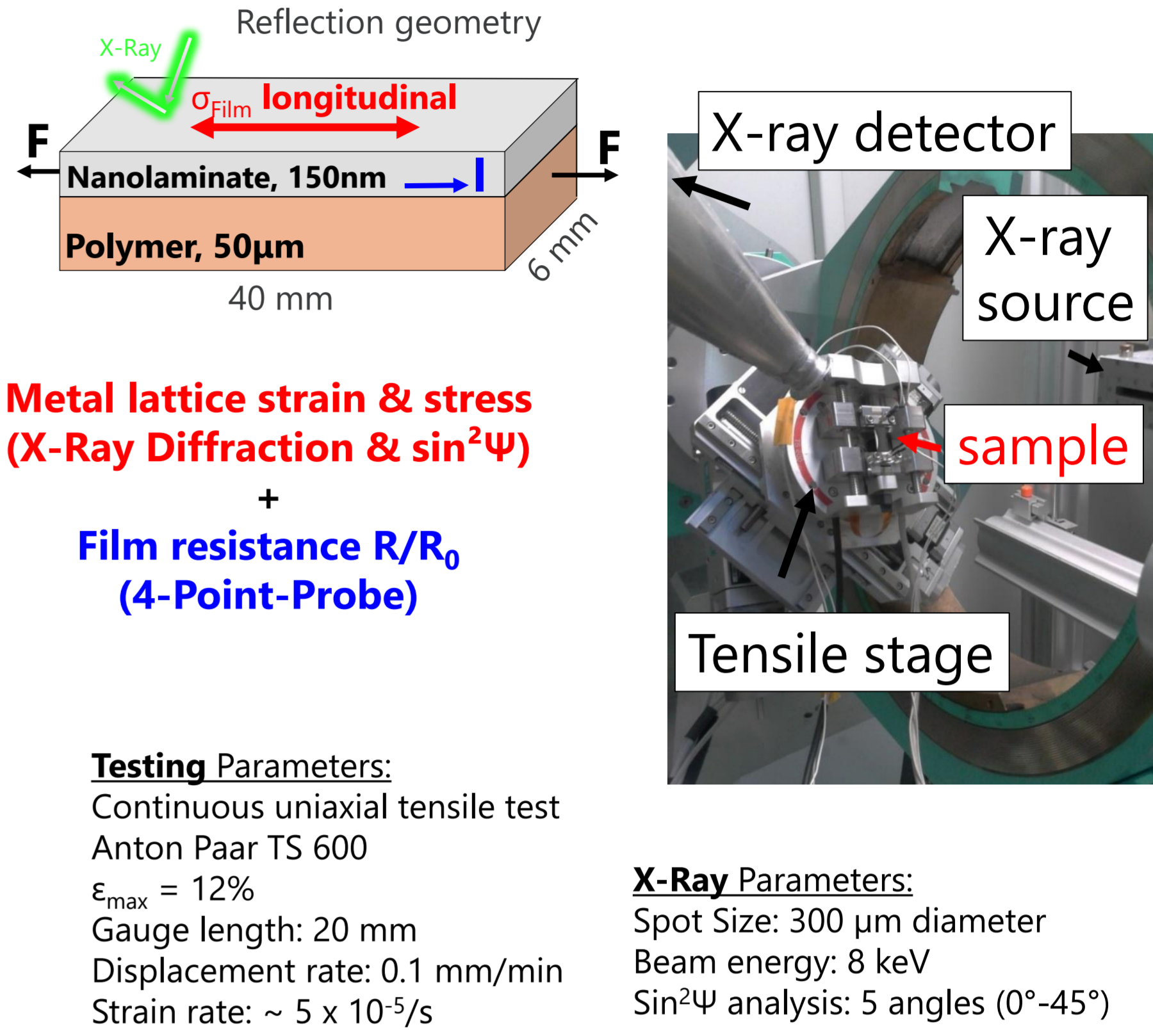
Deformation of flexible nanolaminates is dominated by the most brittle component. Cracks in the brittle layers cause ductile layers to fracture at low strains. Embrittlement depends on the modulation period ( $t_{\text{brittle}} + t_{\text{ductile}}$ ) and ratio ( $t_{\text{brittle}}/t_{\text{ductile}}$ ) [1]. The ALD/PVD process with vacuum transfer opens up a wide range of otherwise unachievable modulation and thickness ratios for metal-oxide nanolaminates. Thickness control with precision down to 0.1 nm can be achieved for Al<sub>2</sub>O<sub>3</sub>, well below the native oxide thickness of pure Al films. Incorporated NPs can further enhance mechanical properties through strengthening or crack deflection.

- Questions addressed:
- How does oxide failure influence deformation of the Al layers?
  - Can we avoid through thickness cracking of Al by reduced oxide layer thicknesses?
  - Can we control grain growth and stabilize nanostructures with monolayers of ALD?
  - Can we strengthen laminates by reducing the metal layer thickness and incorporating NPs?

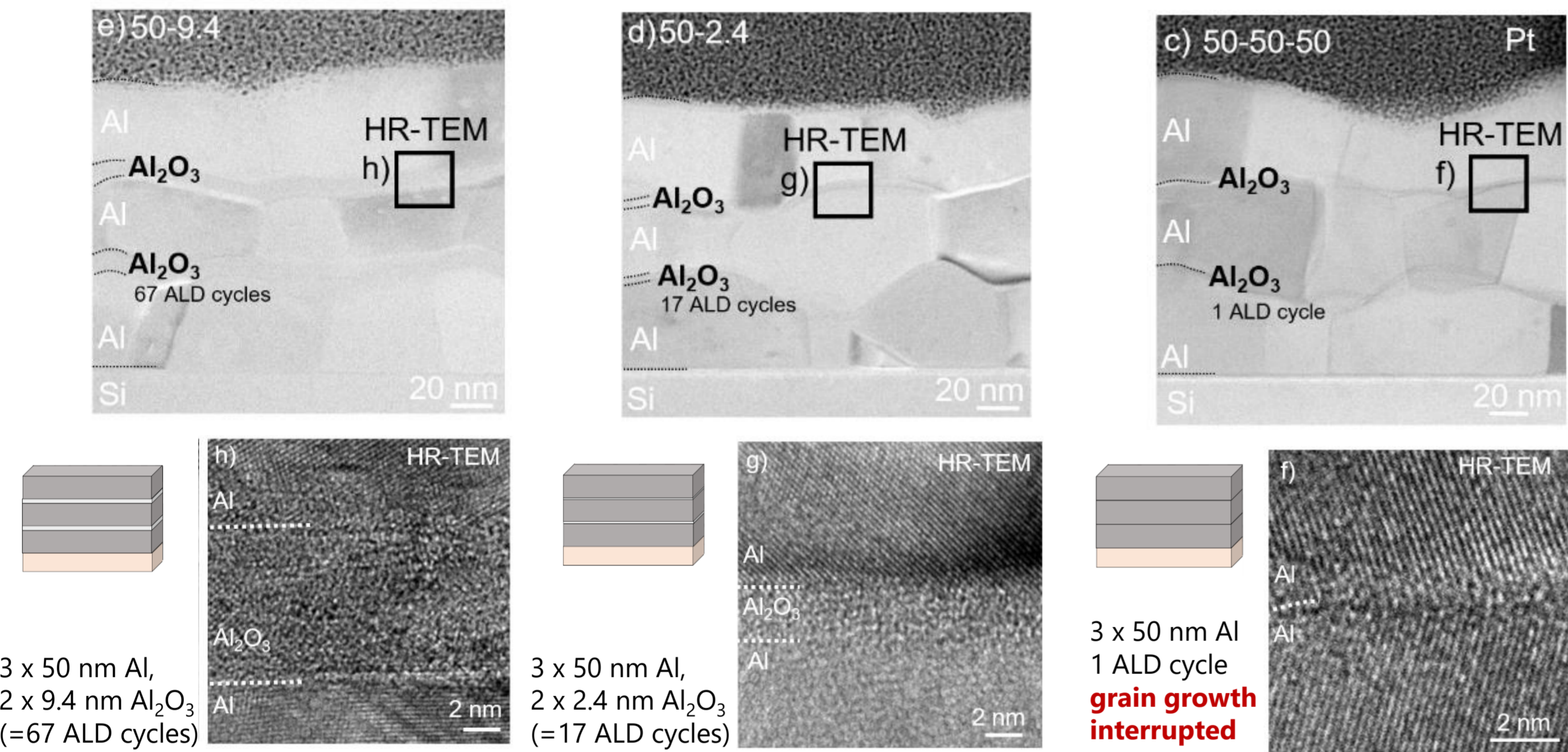
## Thin film deposition



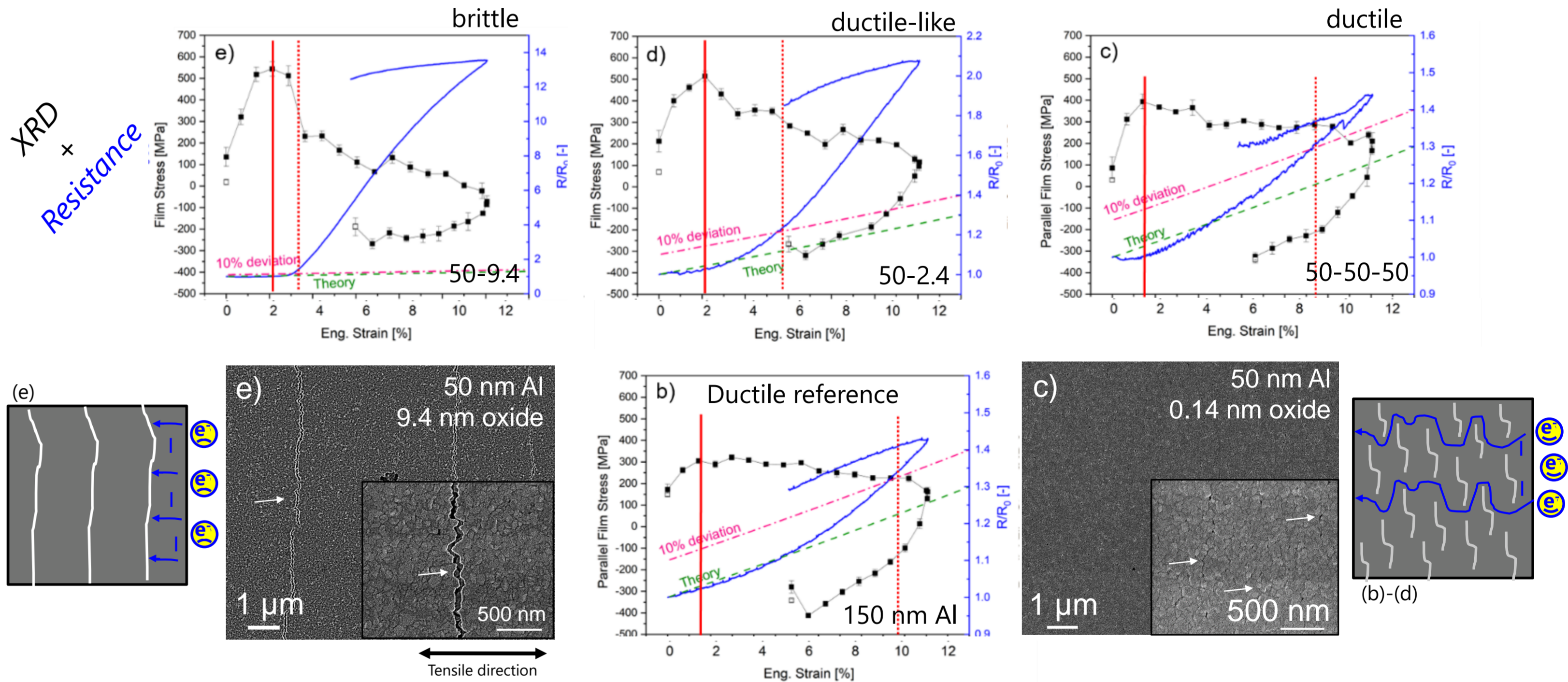
## In situ<sup>2</sup> film stress measurements



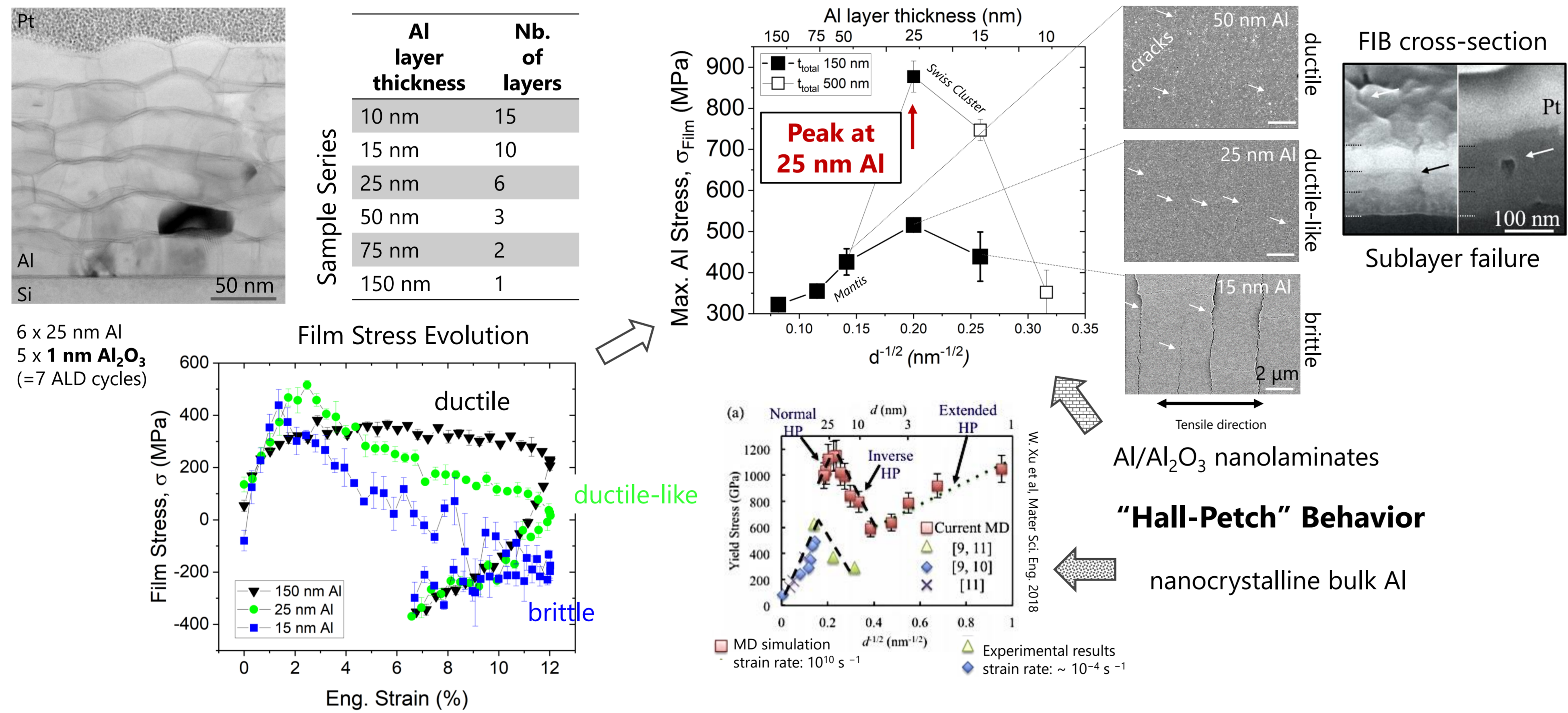
## I) 150 nm Al/Al<sub>2</sub>O<sub>3</sub> nanolaminates - Variation of Oxide Layer Thickness



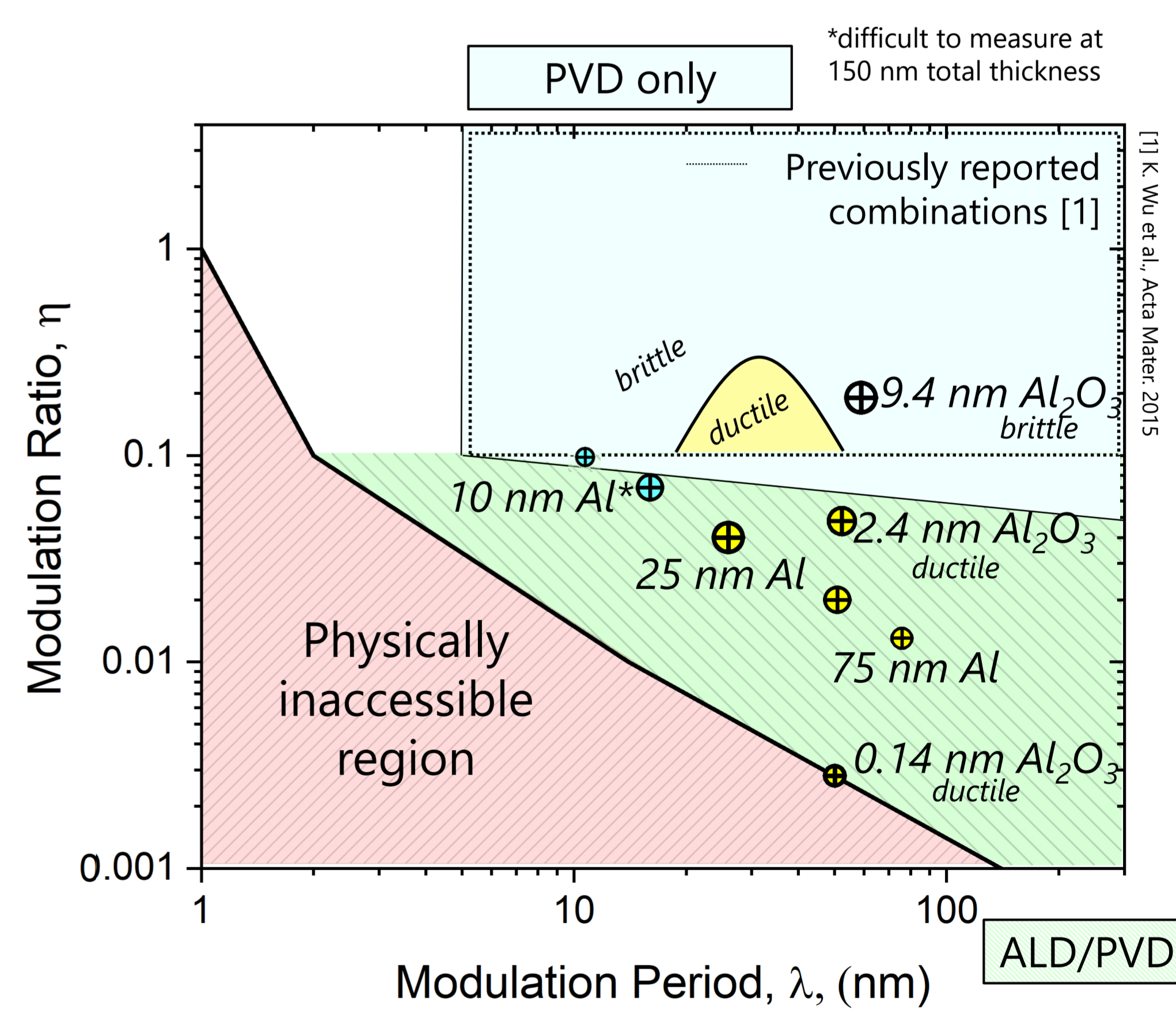
## Electro - Mechanical Behavior



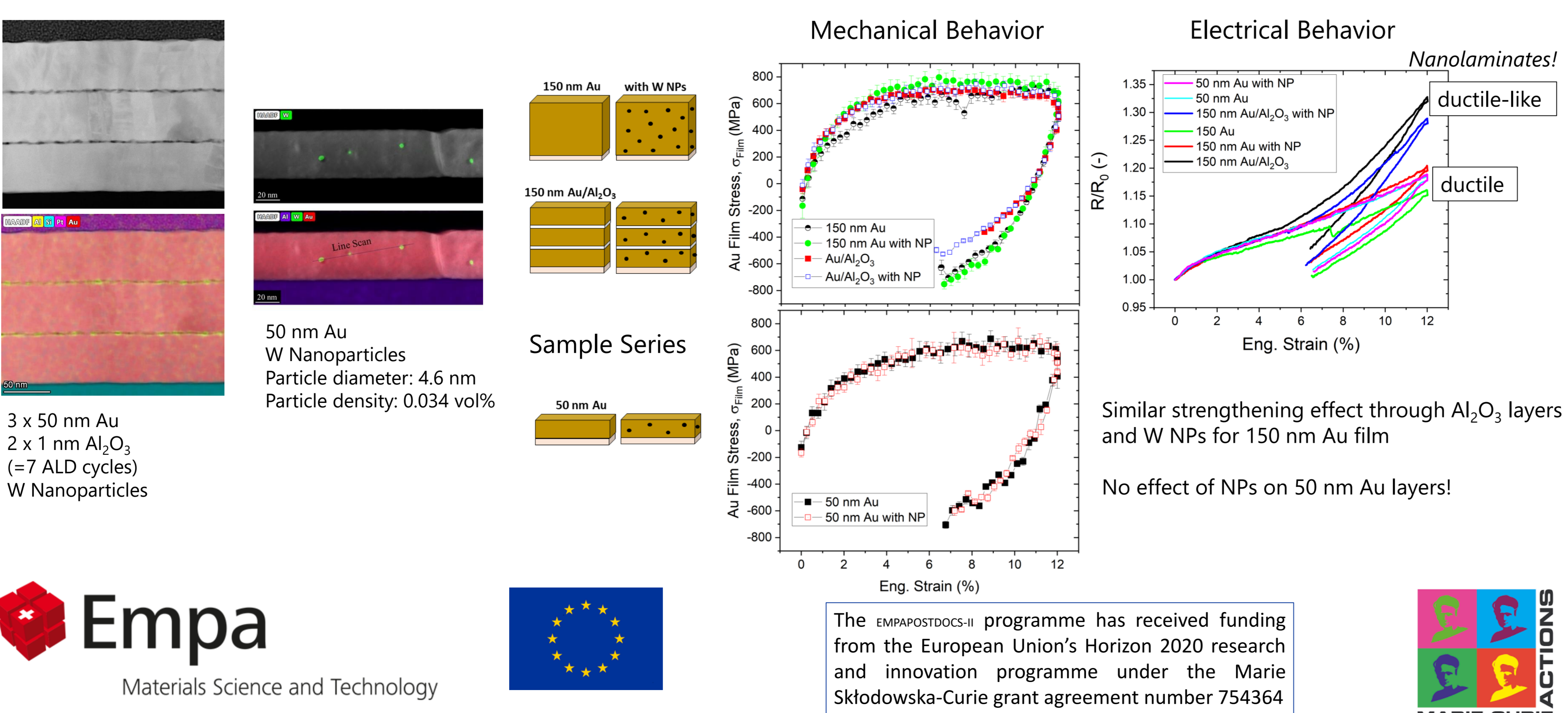
## II) 150 nm Al/Al<sub>2</sub>O<sub>3</sub> nanolaminates – Variation of Metal Layer Thickness



## Extended Deformation Map (I+II)



## III) 150 nm Au/Al<sub>2</sub>O<sub>3</sub> nanolaminates with W nanoparticles



## Conclusions (I-III)

- Al grain size can be controlled by 1 cycle of ALD
- Improved lateral and through thickness damage tolerance with decreasing oxide layer thickness
- No embrittlement for Al<sub>2</sub>O<sub>3</sub> ≤ 2.4 nm
- Maximum strength achieved with 25 nm Al layer thickness
- At 25 nm Al thickness ductile-like failure is maintained
- Nanoparticles and Al<sub>2</sub>O<sub>3</sub> layers yield similar strength increase for 150 nm Au films
- No effect of nanoparticles observed in thinner, 50 nm Au films