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INDENTATION BEHAVIOR OF MULTILAYERED THIN FILMS: EFFECTS OF LAYER UNDULATION

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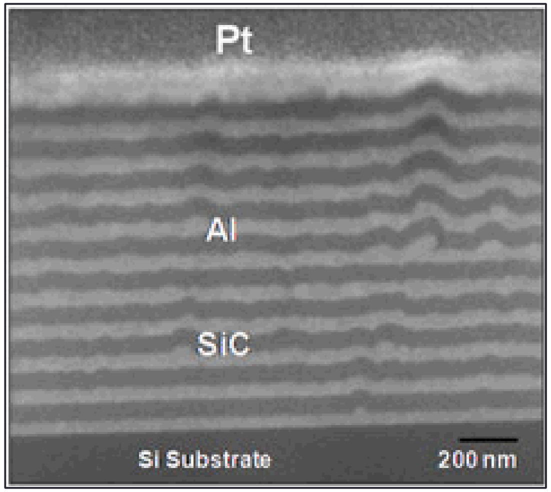
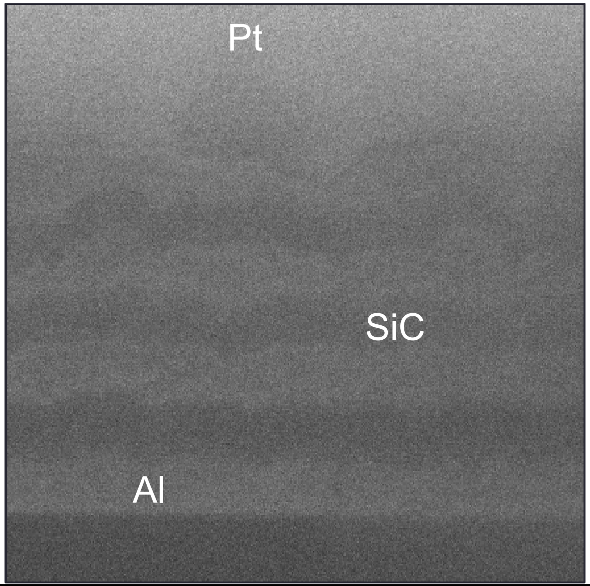
The Effects of Layer Undulation on Nanoindentation Response

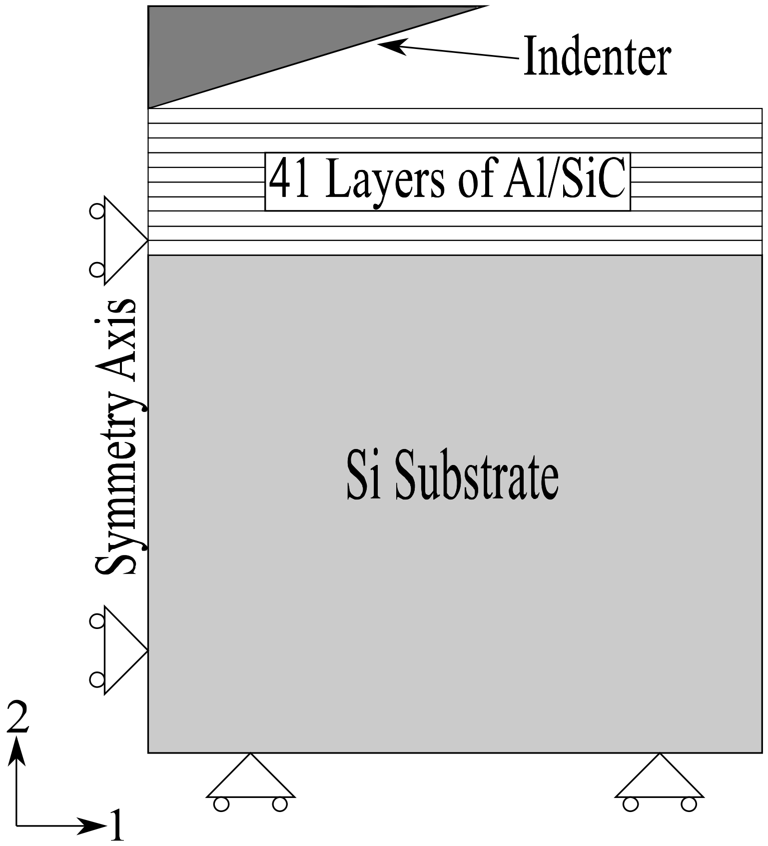
- Thin film characterization rely on nanoindentation
- Unique and complicated nanoindentation response
- Wavy pattern apparent in multilayer thin-films
- Granular structure of soft material during fabrication
- Sensitivity of indentation derived values





Model Description

- 41 alternating layers of Al/SiC on Si substrate
- Conical indenter
- 40 μm x 43 μm
- 50 nm layer
- Axisymmetric
- μ = 0.1



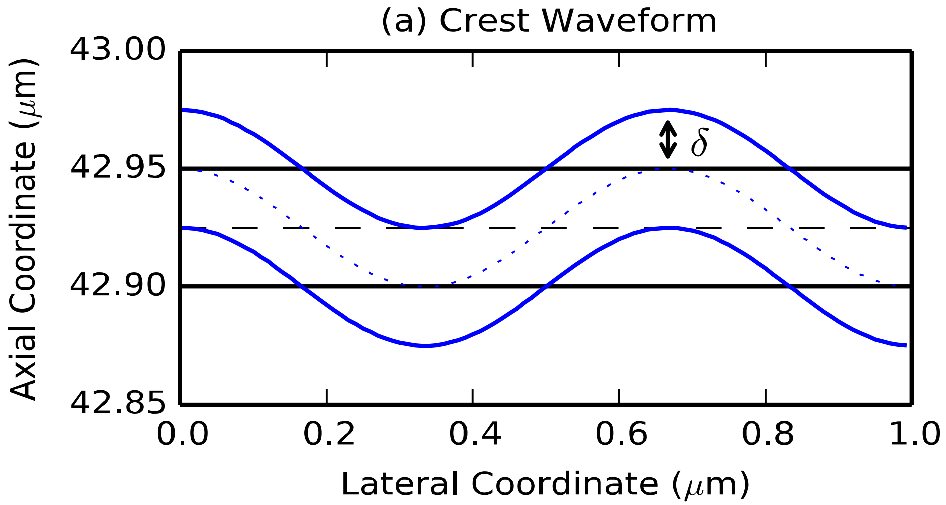
Material Properties

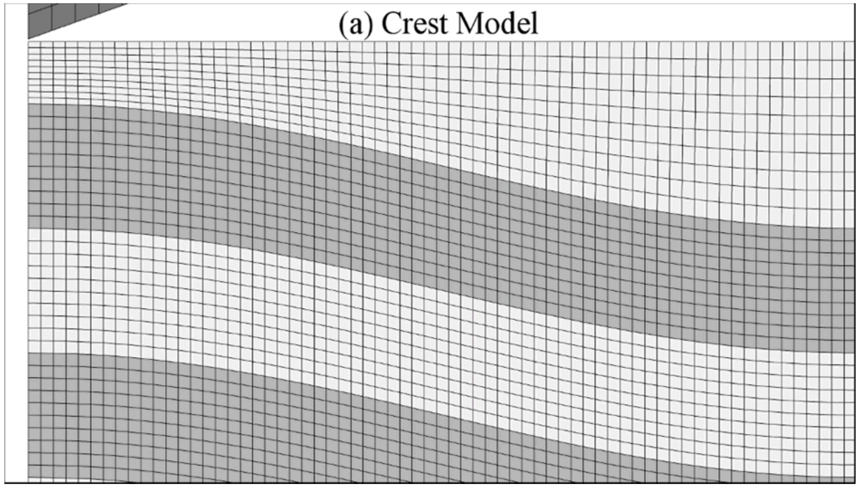
- Aluminum (Al): elastic-plastic
- Silicon Carbide (SiC): elastic-perfectly-plastic
- Silicon (Si) Substrate: elastic
- Diamond Indenter: elastic
- Additional assumptions:
  - Isotropic
  - von Mises yield criterion
  - Rate independent

	Aluminum	Silicon Carbide	Silicon	Diamond
Young's Modulus (GPa)	59	277	187	1,141
Poisson's Ratio	0.33	0.17	0.28	0.07
Yield Strength (MPa)	200	8770	--	--

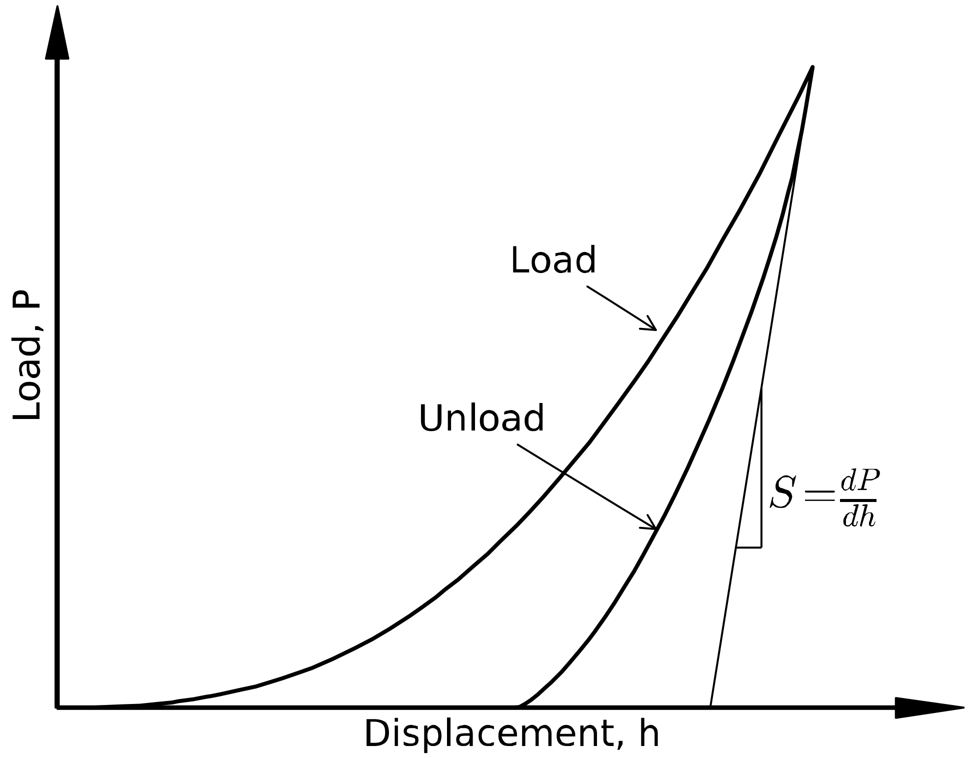
Undulating Features

- Two versions
  - “Crest”
  - “Trough”
- Amplitude (δ): 12.5 & 25 nm
- Wavelengths: 200, 400, 667 nm
- ~125,000 elements





Derivation



Elastic Modulus

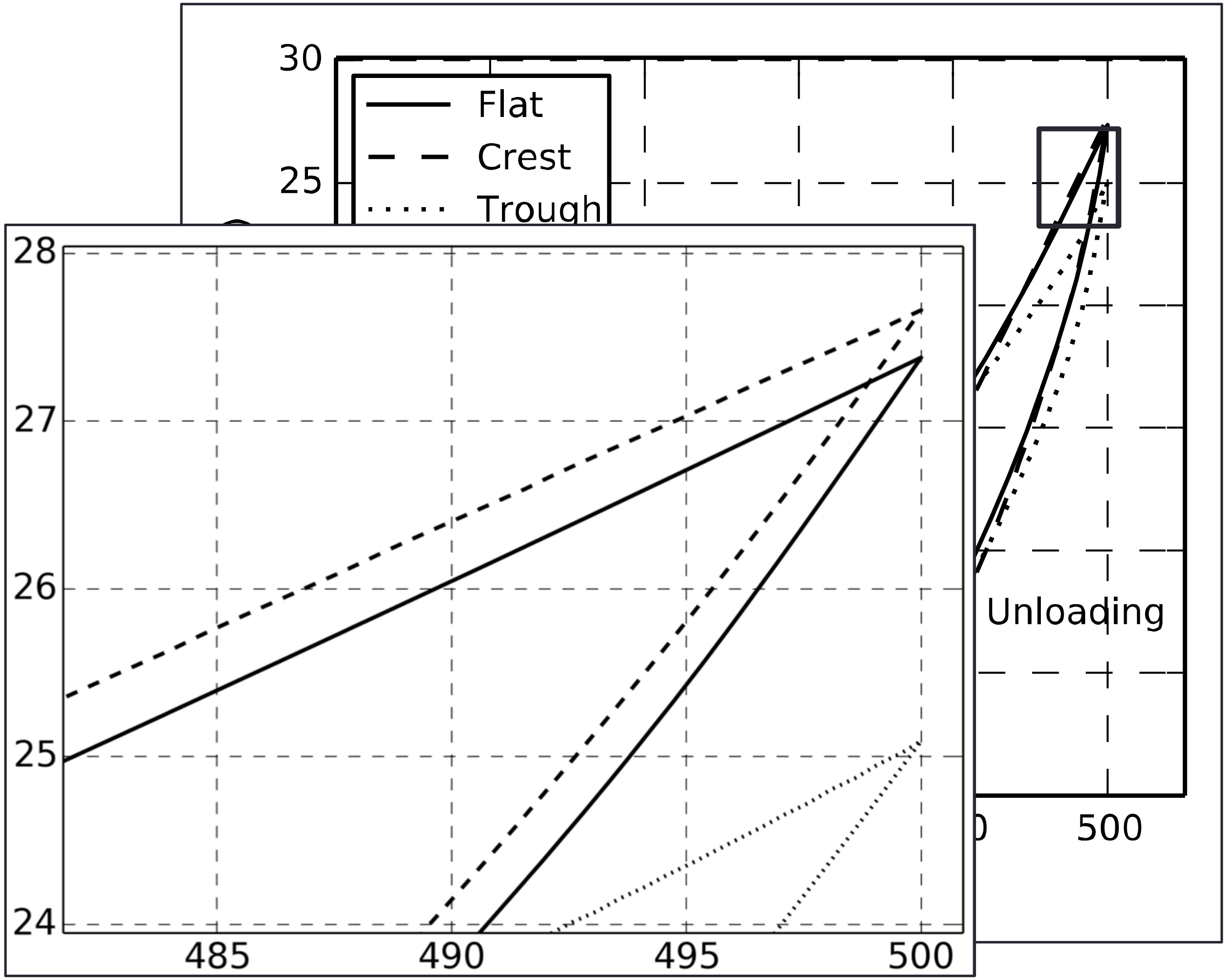
$$S = \beta \frac{2}{\sqrt{\pi}} E_{eff} \sqrt{A}$$

$$\frac{1}{E_{eff}} = \frac{1-\nu^2}{E} + \frac{1-\nu_i^2}{E_i}$$

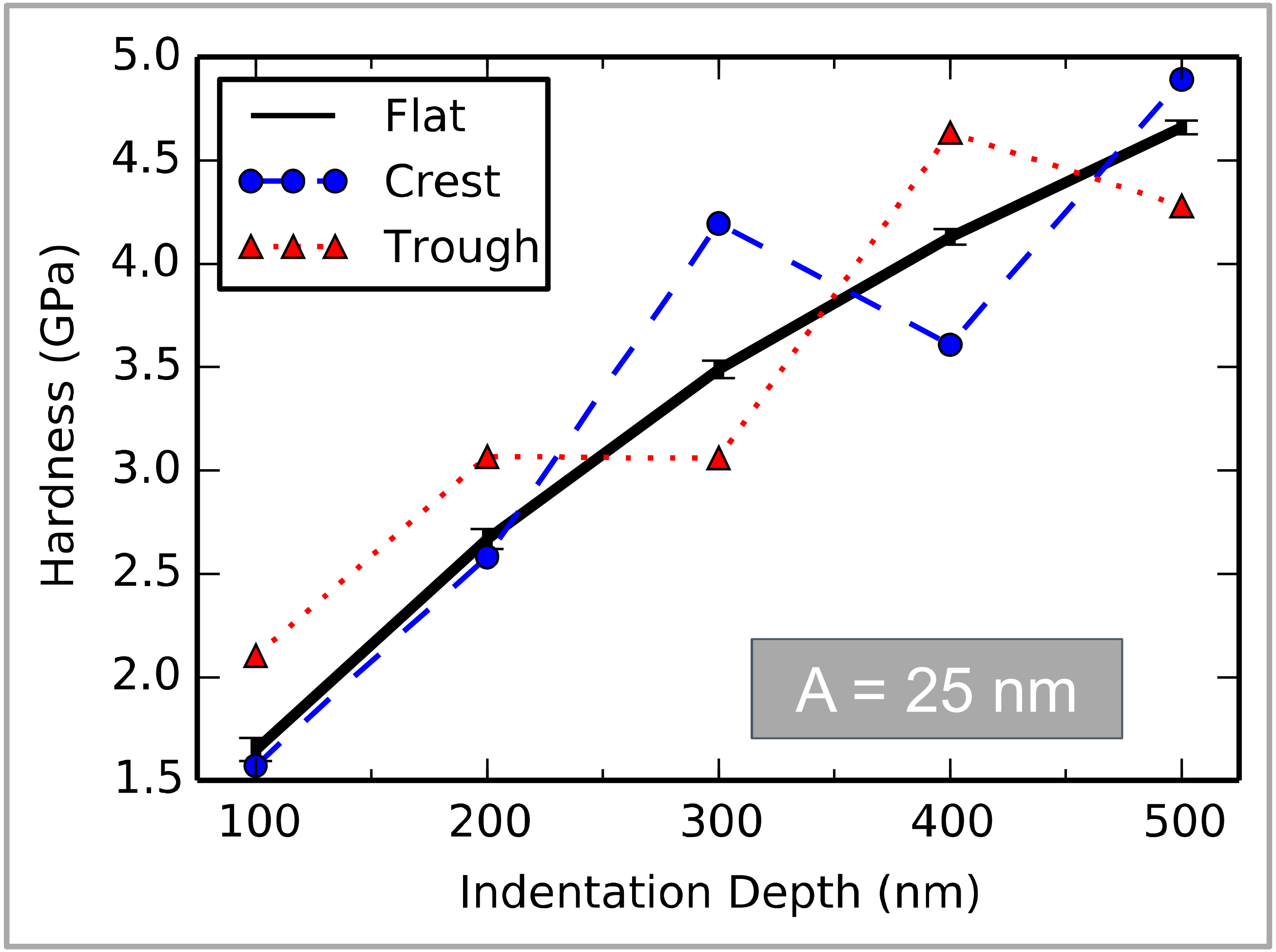
Hardness

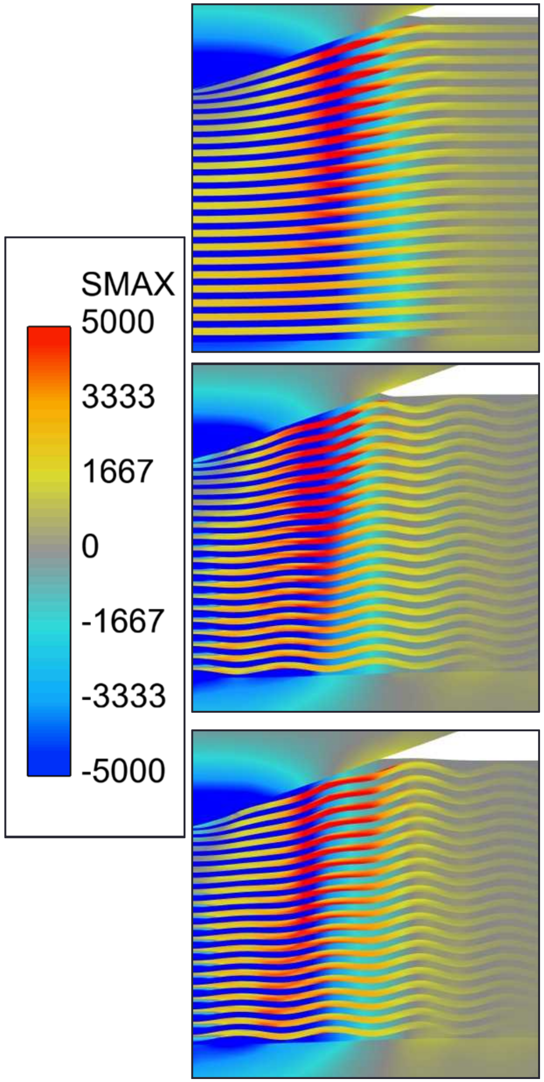
$$H = \frac{P_{Peak}}{A}$$

Load-Displacement Response

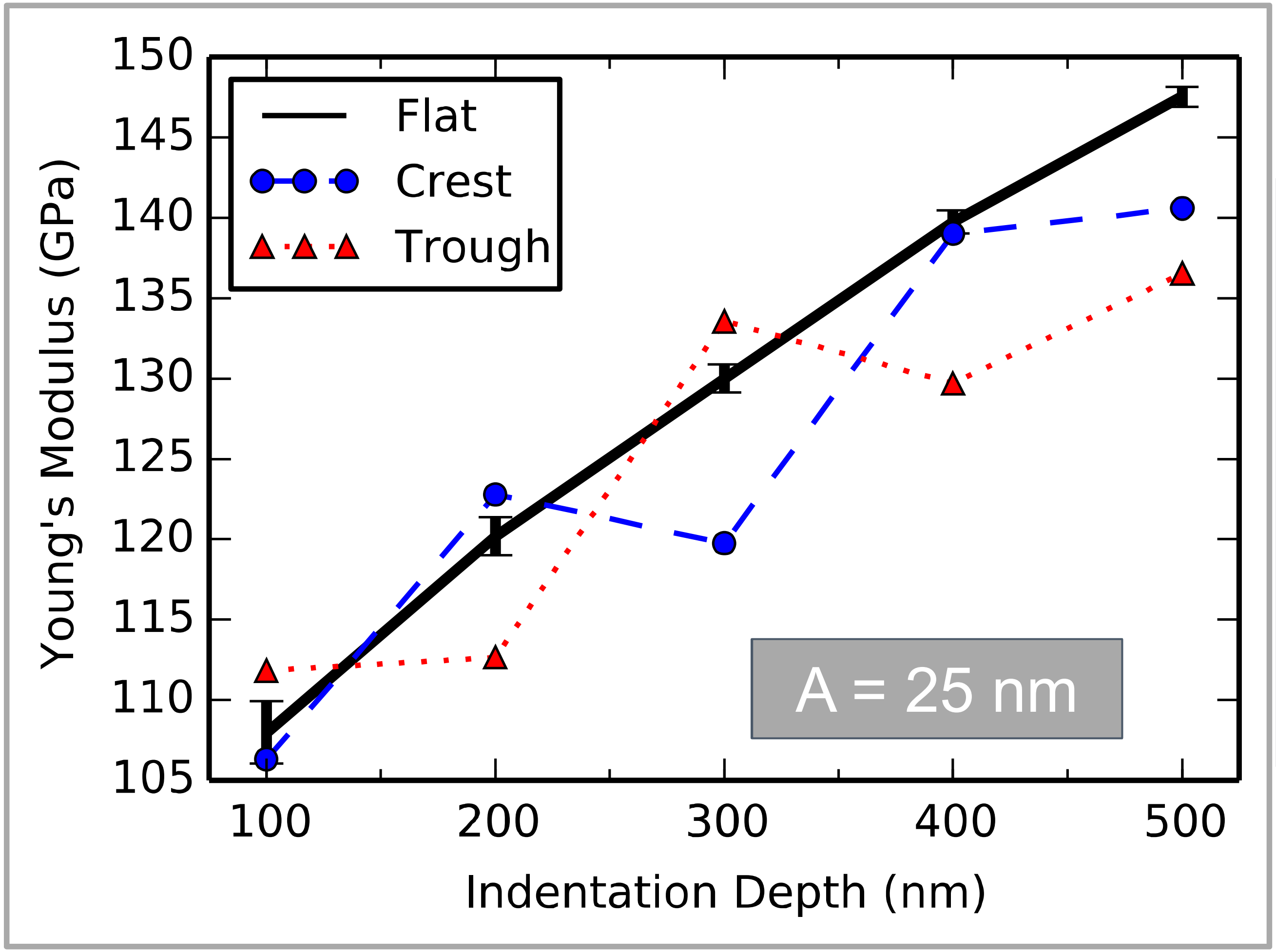


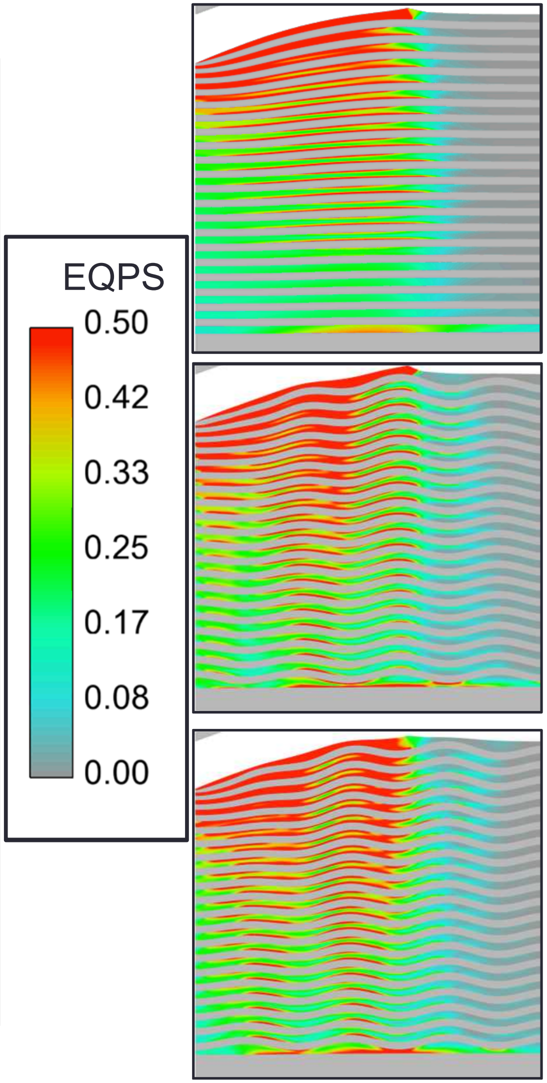
Indentation Derived Hardness





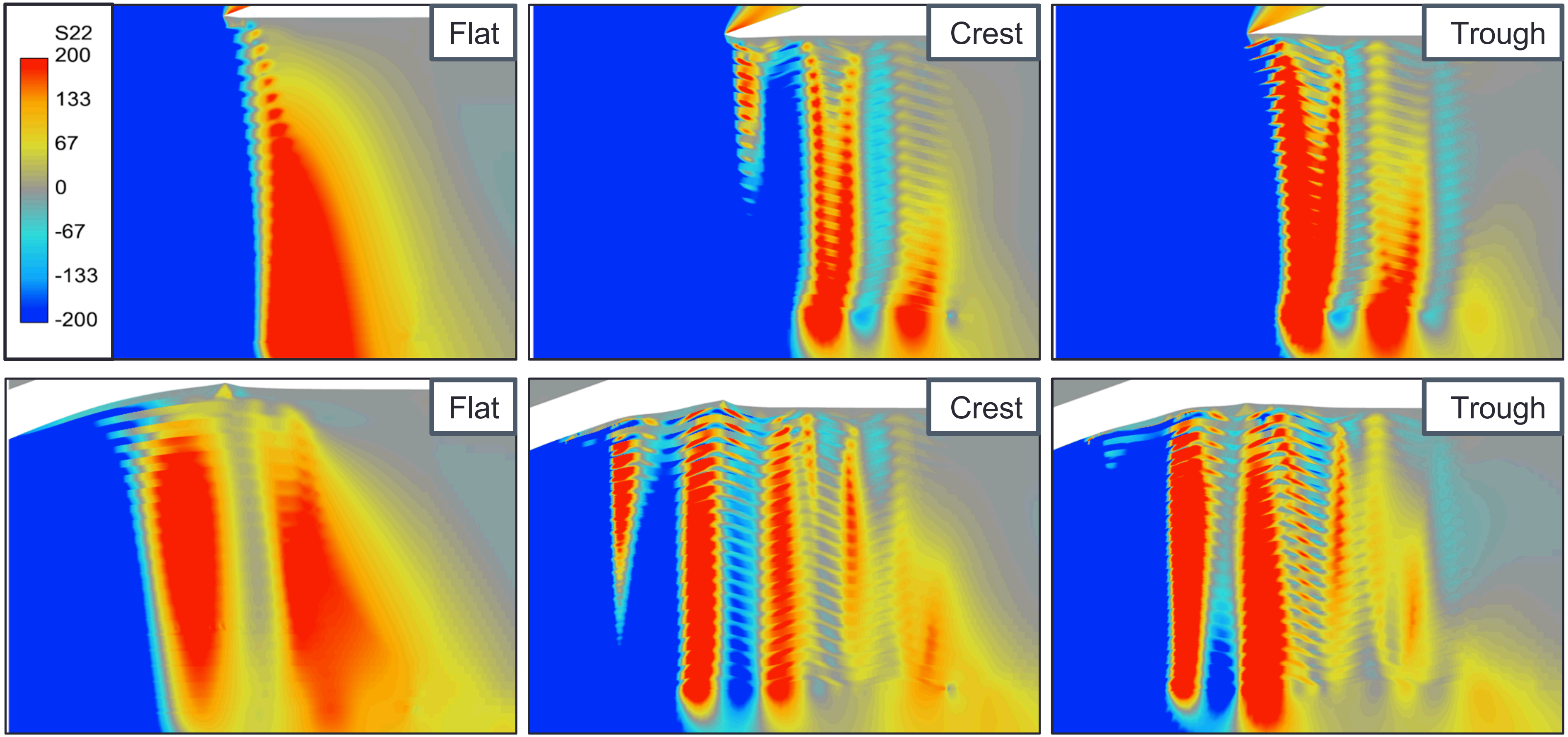
Indentation Derived Modulus





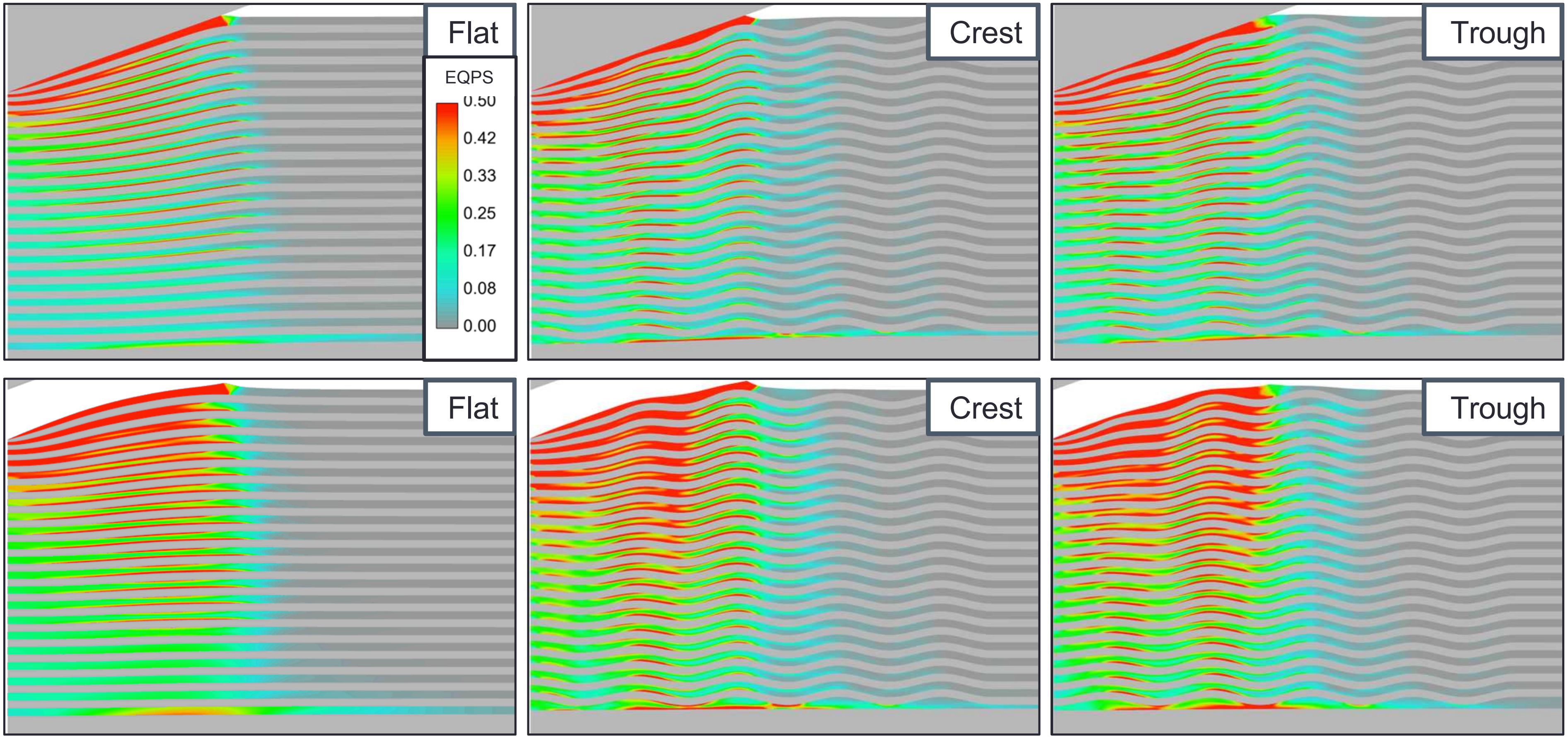
Axial Stress (σ_{22} – MPa) @ 500 nm

Increased axial tensile stresses generated from compressive loading with undulation



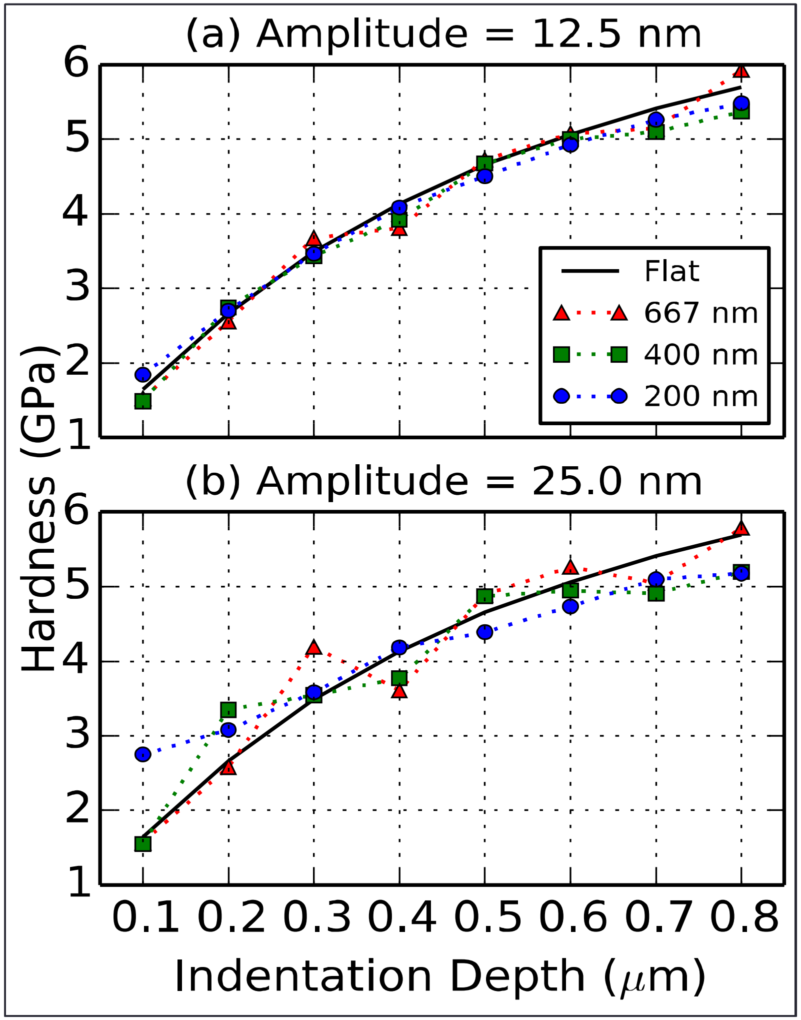
Equivalent Plastic Strain in Al @ 500 nm

Undulations enhance the unloading induced plastic strain

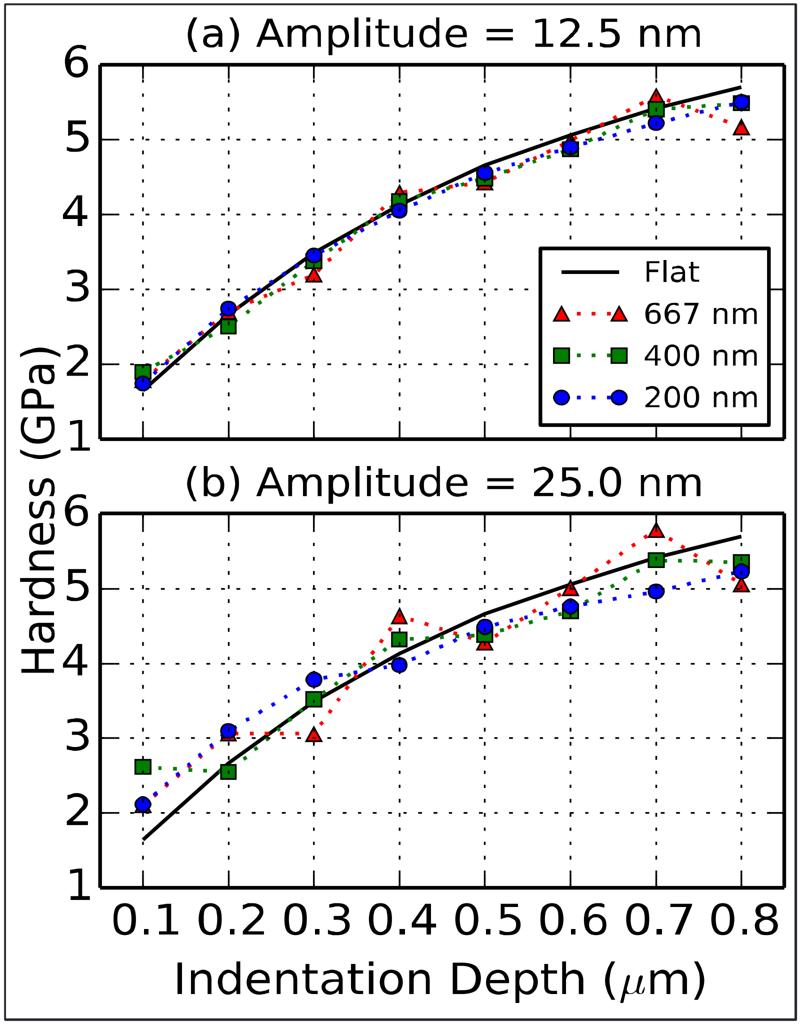


Derived Hardness

Crest

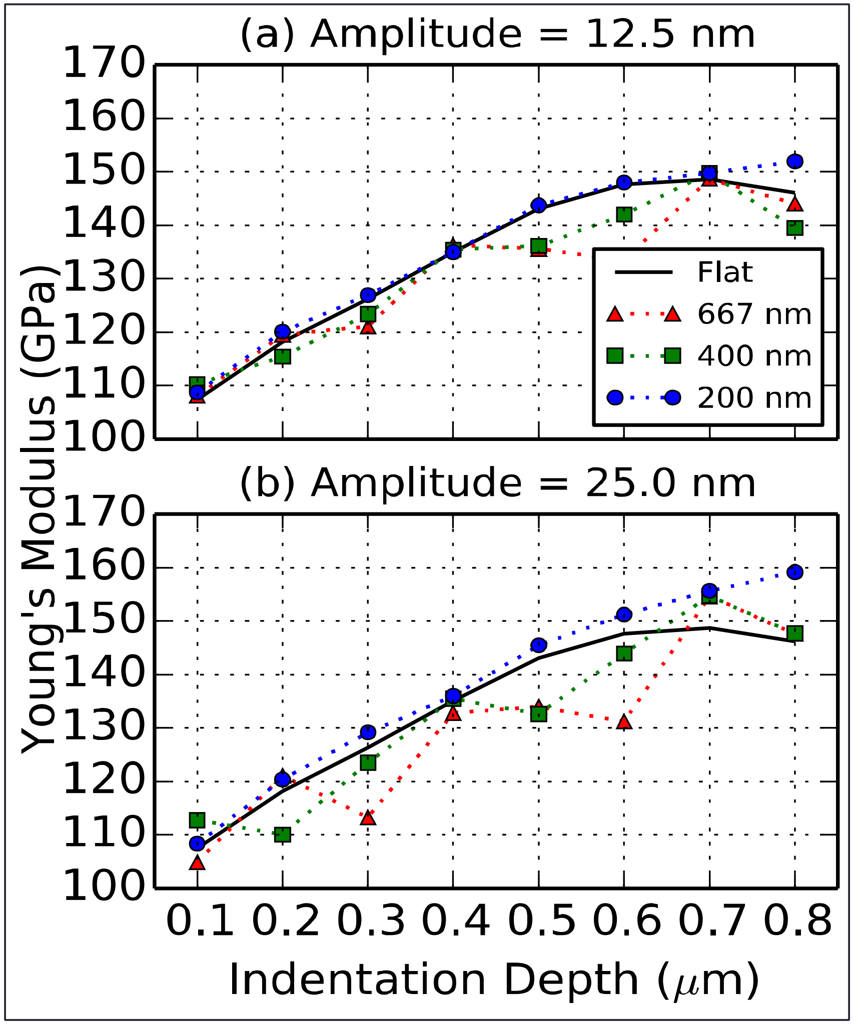


Trough

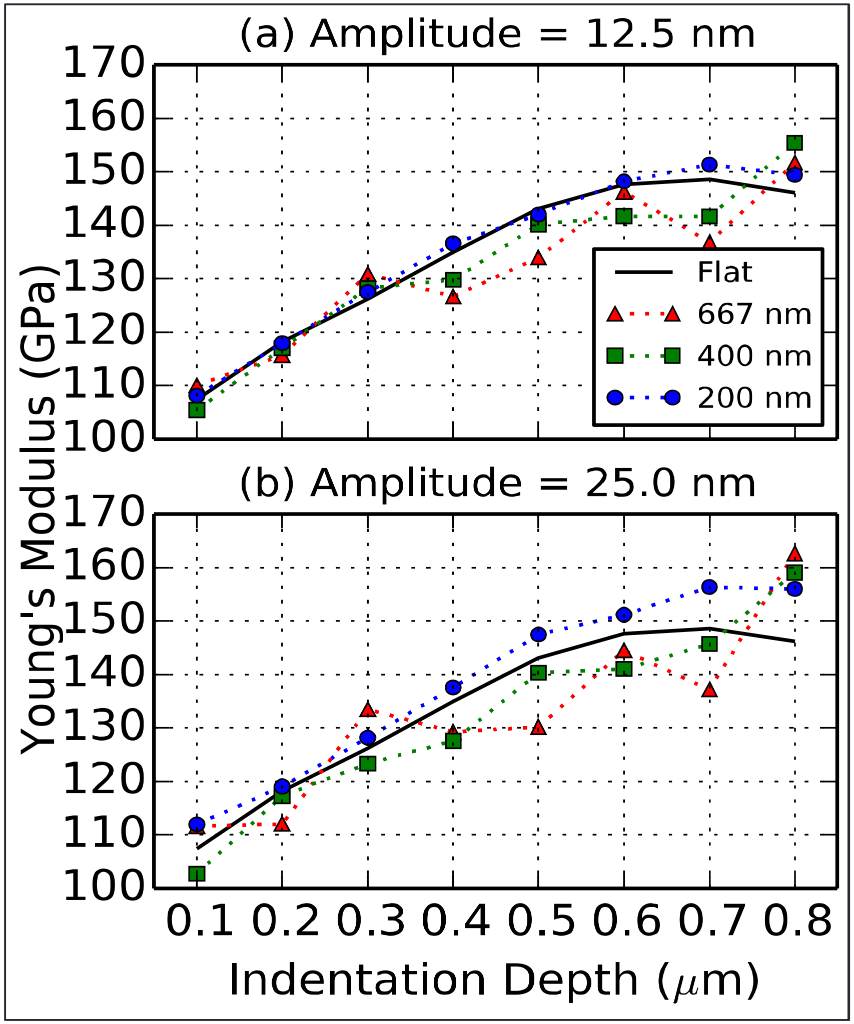


Derived Modulus

Crest

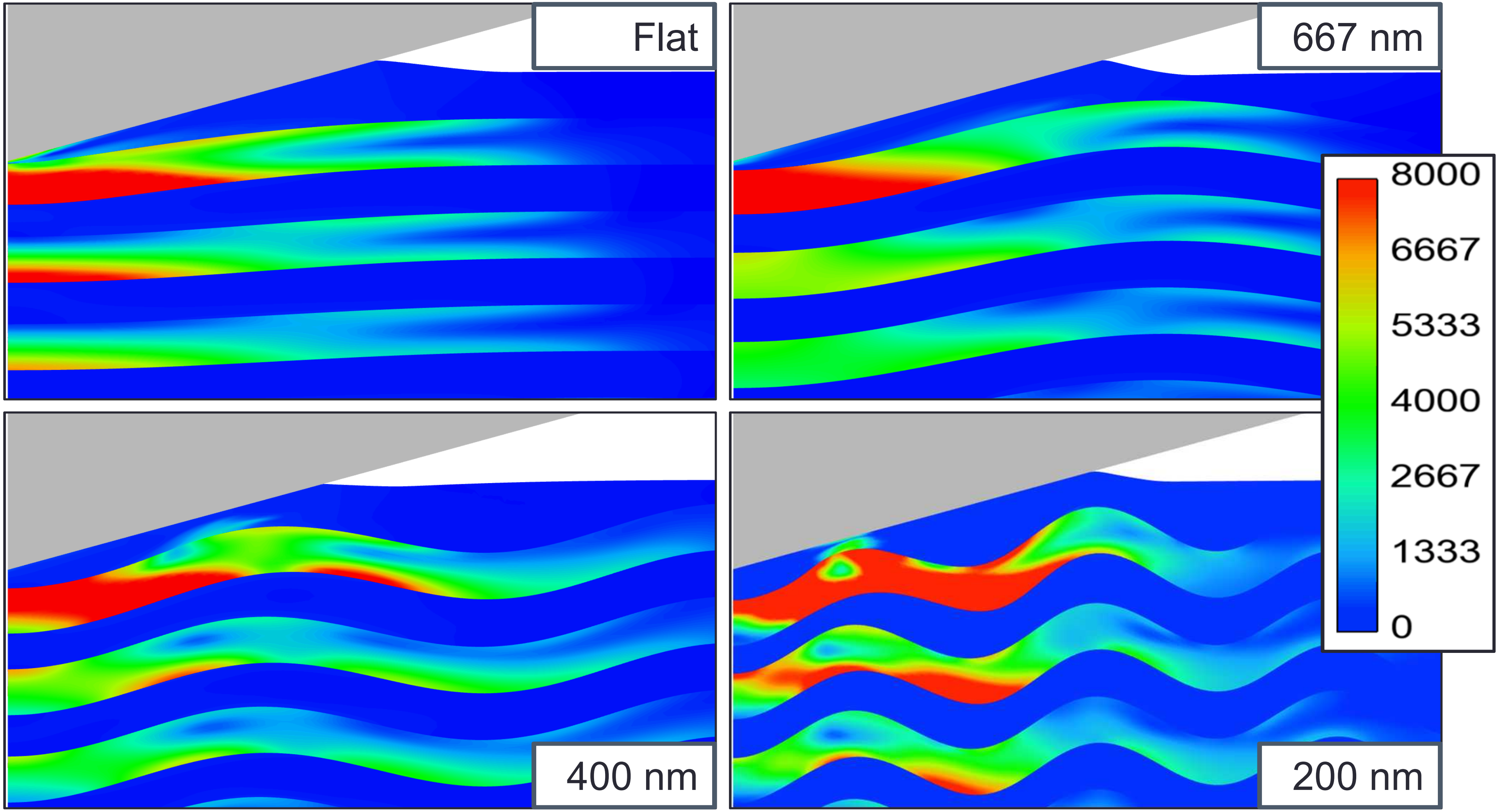


Trough



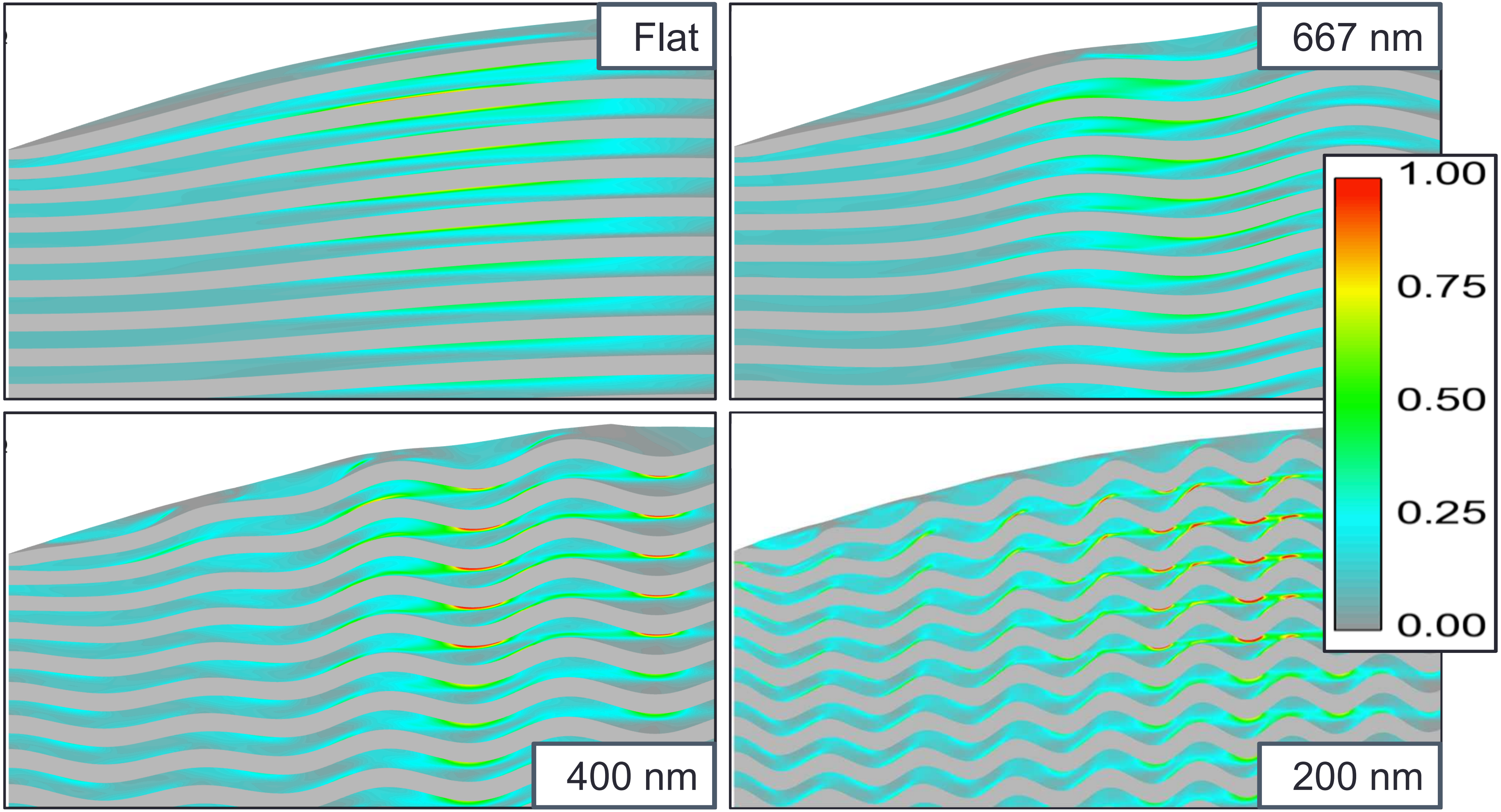
von Mises Stress (MPa)

Undulations redistribute and result in complex stress fields

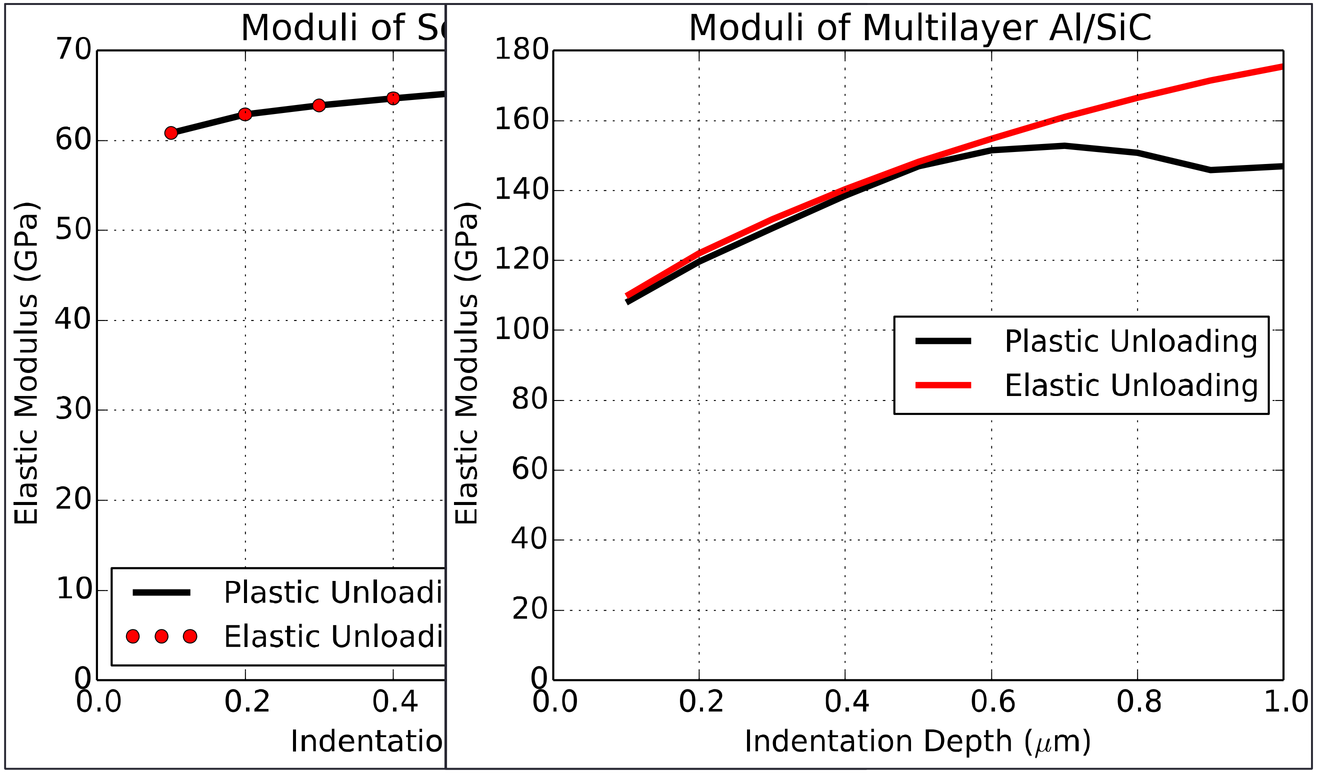


Change in Plastic Strain (ΔEQPS)

Undulations effect the unloading induced plasticity



Forced Elastic Unloading



Unloading-induced plasticity does affect the indentation-derived modulus for multilayer thin films

Conclusions

- Sensitivity of undulating layers
  - λ = 200, 400, & 667 nm
  - δ = 12.5 & 25.0 nm
  - Crest & trough

- Indentation derived hardness and modulus
  - Deviation of nearly 10%
  - Orientation dependent

- Indentation induced plastic strain
  - Loading and unloading strain increases

Wavy Multilayer Moduli

Voigt & Reuss models, assuming 1D, results in moduli of:

E_{11} = 166 GPa
E_{22} = 96 GPa