Fast simulation of pattern dependencies in thermal nanoimprint lithography

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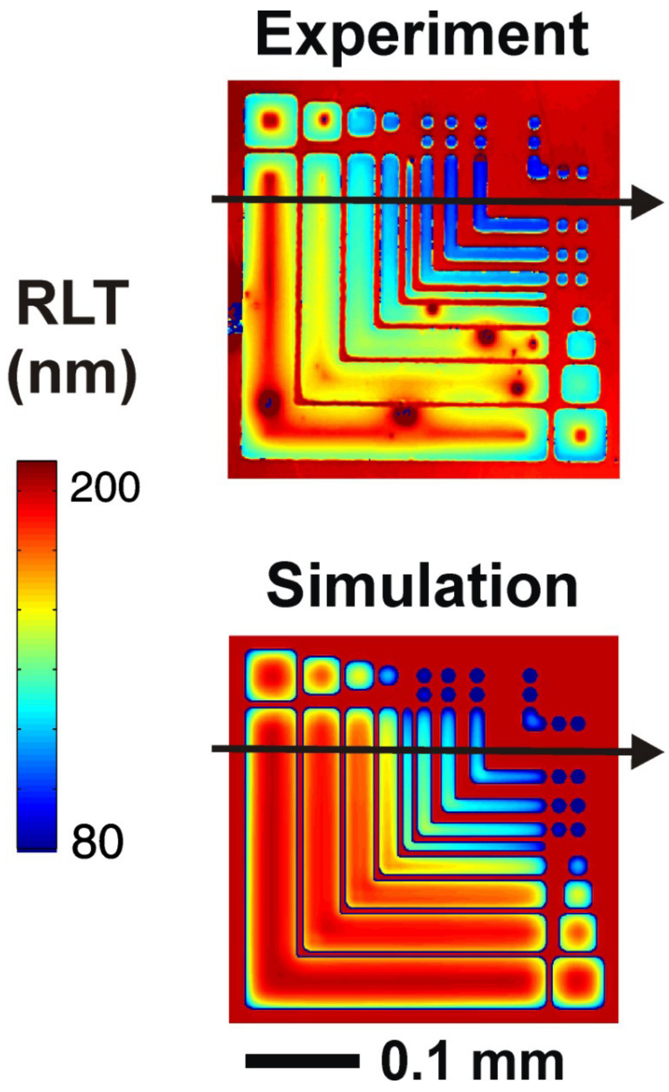
Hayden Taylor and Duane Boning
Massachusetts Institute of Technology

SMA Singapore-MIT Alliance

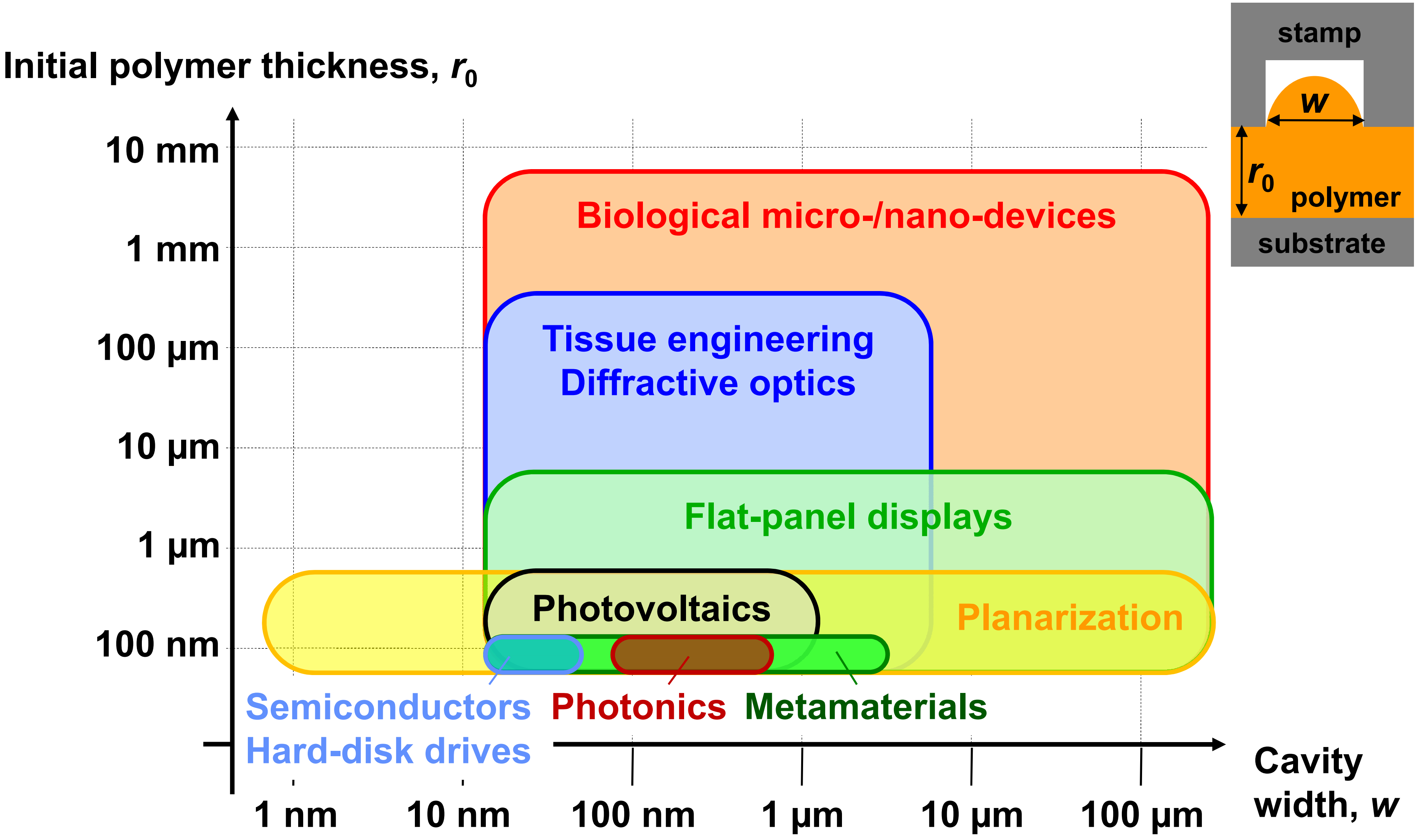
THE IET AWARDS 2009
INNOVATION FINALIST

Nanoimprint modeling needs

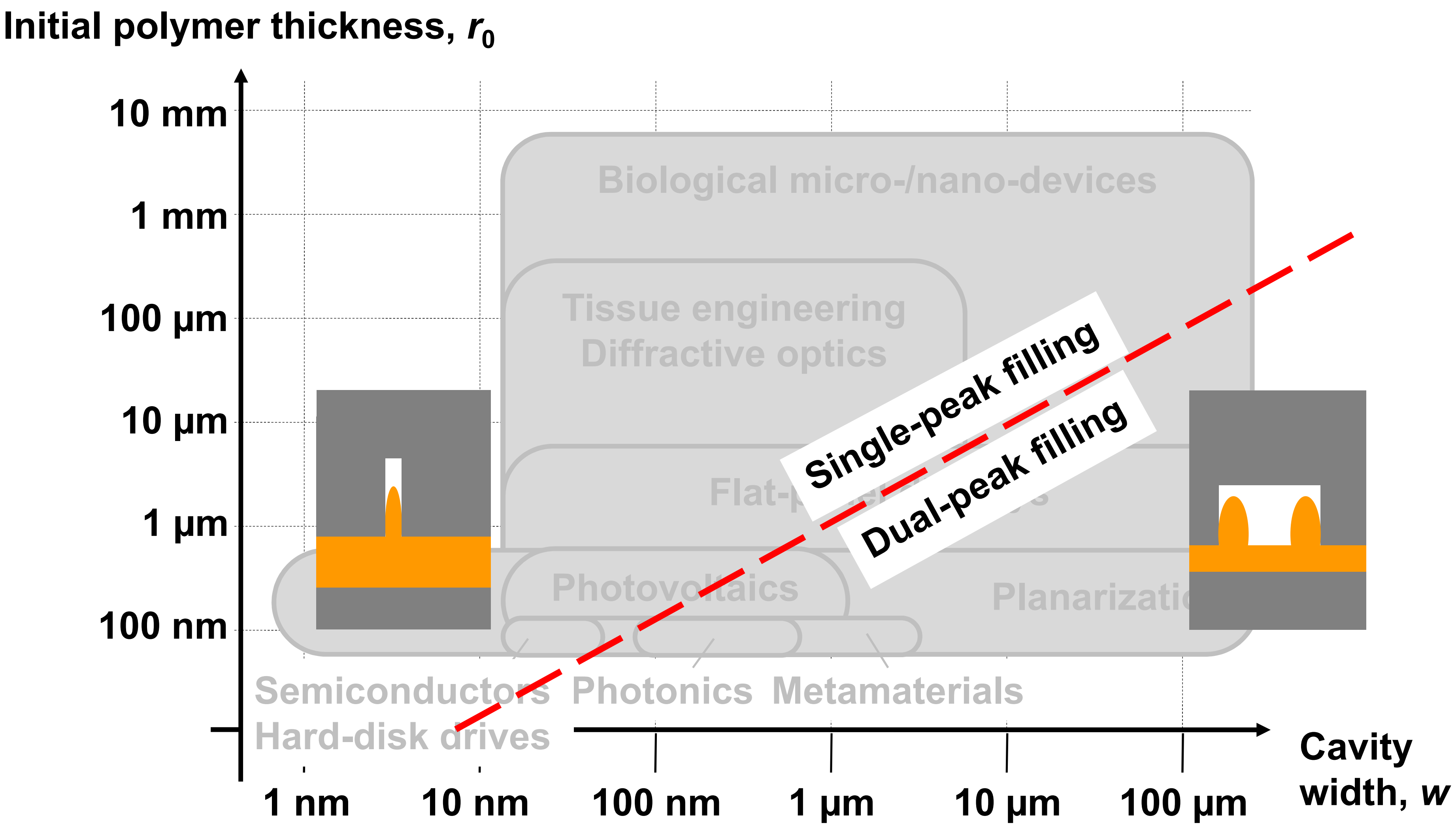


- **Cell-level**
  - Hundreds of features
  - Guide iterative layout design
  - Desktop processing in minutes
- **Chip-level**
  - Many millions of features
  - Pre-fabrication check: overnight?
  - Guide process selection
- **Need for flexibility**
  - Rapid innovation in resist and stamp materials
  - Richness of geometries

We need a unified simulation approach for micro- and nano-embossing/imprinting

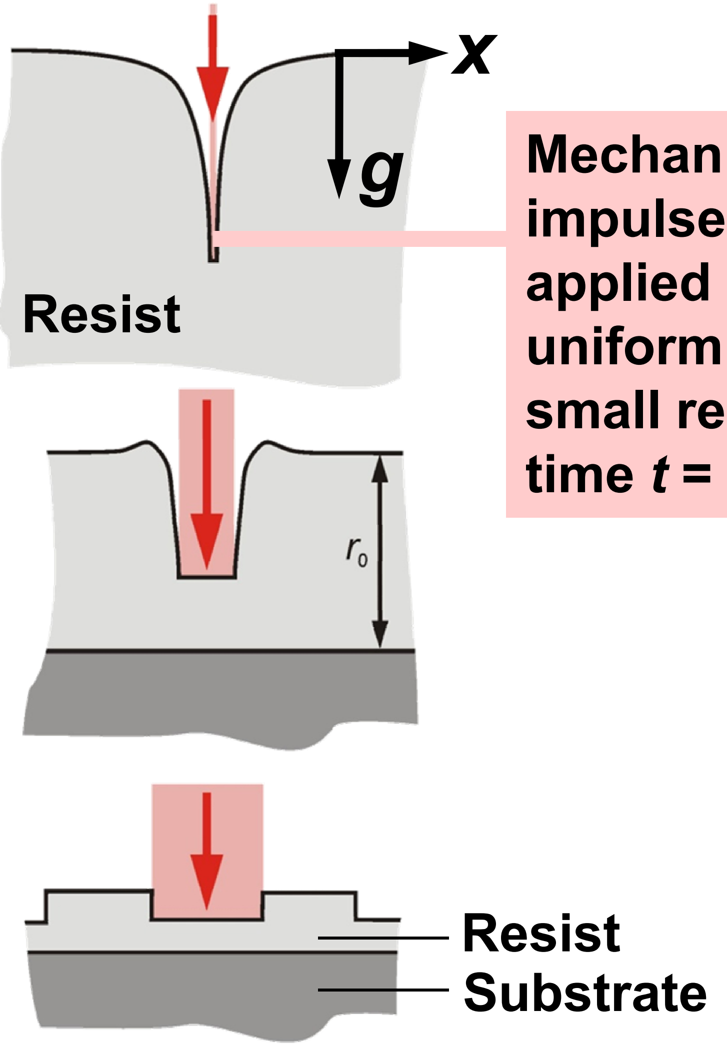


We need a unified simulation approach for micro- and nano-embossing/imprinting



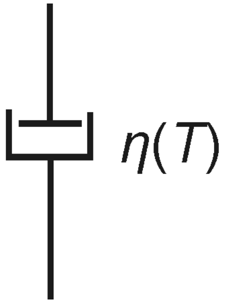
Key: model impulse response $g(x,y,t)$ of resist layer

Model in space:

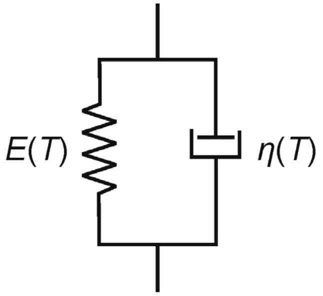


Mechanical impulse applied uniformly over small region at time $t = 0$

Model in time:



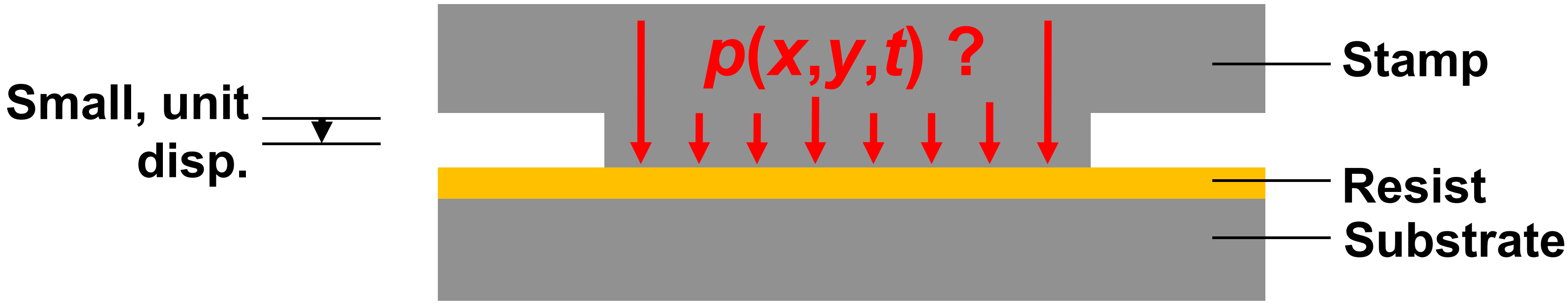
Newtonian: impulse response constant in time for $t > 0$



Viscoelastic: impulse response is function of time.

After Nogi *et al.*, *Trans ASME: J Tribology*, **119** 493-500 (1997)

Change in topography is given by convolution of impulse response with pressure distribution

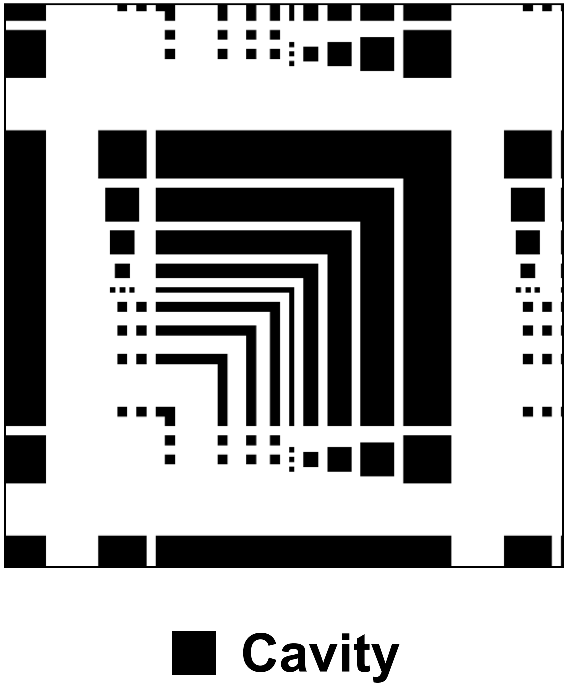


$$\left[\underbrace{p(x,y,t)}_{\text{Pressure } ?} * \underbrace{g(x,y,t)}_{\text{Impulse response}}\right]\overset{\text{Time increment}}{\Delta t} = \underbrace{\mathbf{1}}_{\text{Unit displacement in contact region}}$$

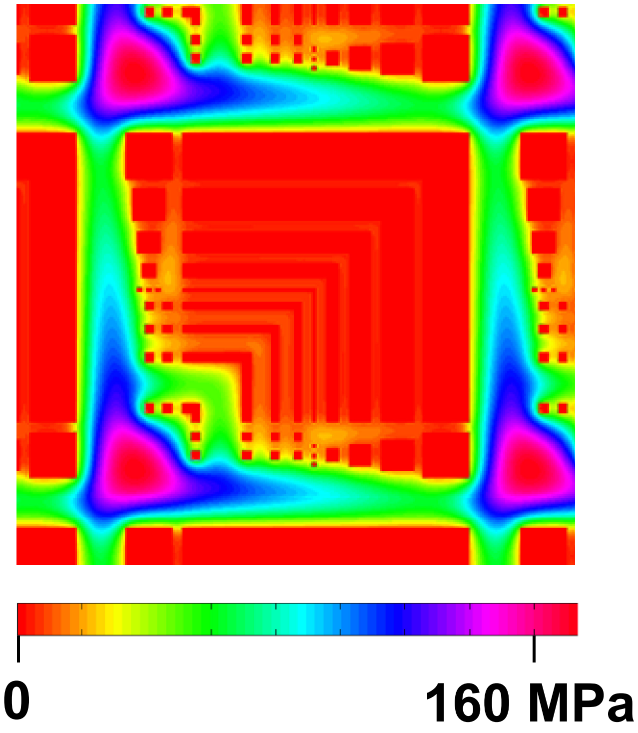
Contact pressure distributions can be found for arbitrary stamp geometries

2.3 µm-thick polysulfone film embossed at 205 °C under 30 MPa for 2 mins

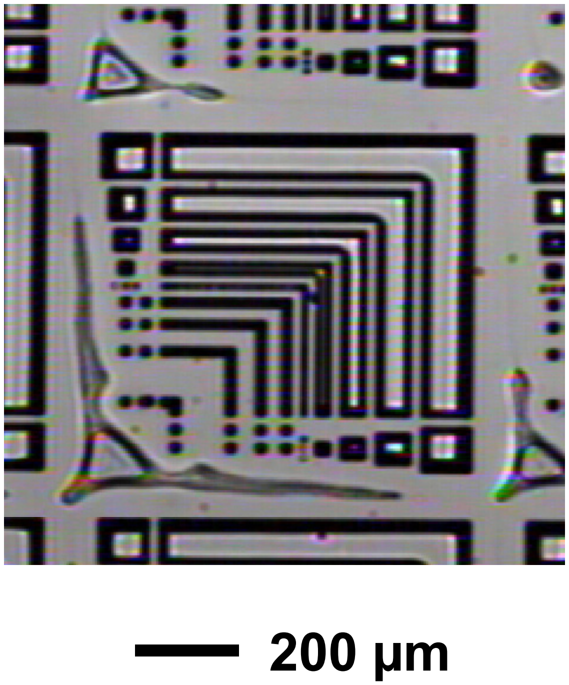
Stamp design



Simulated pressure



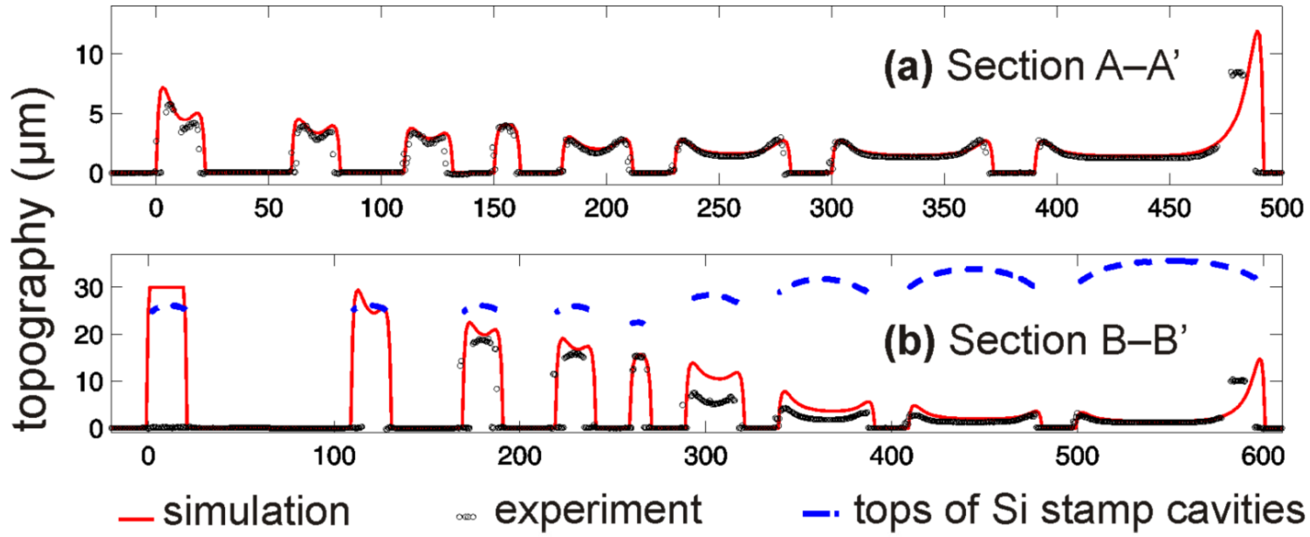
Optical micrograph

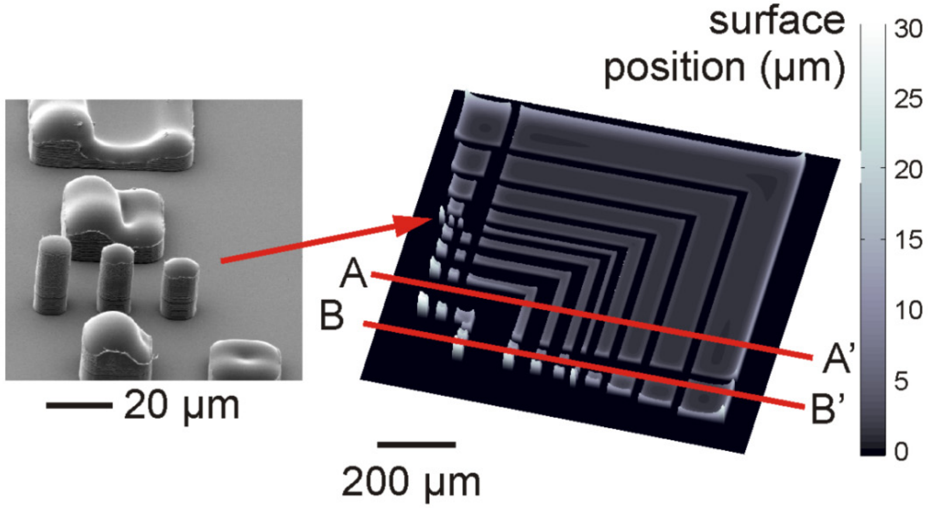


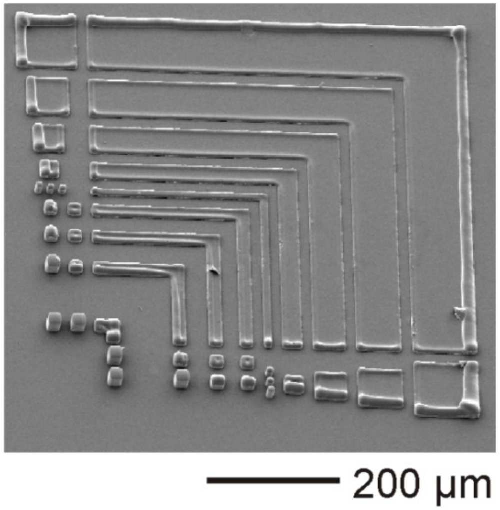
Taylor *et al.*, SPIE 7269 (2009).

Successful modeling of polysulfone imprint

2.3 µm-thick polysulfone film embossed at 205 °C under 30 MPa for 2 mins

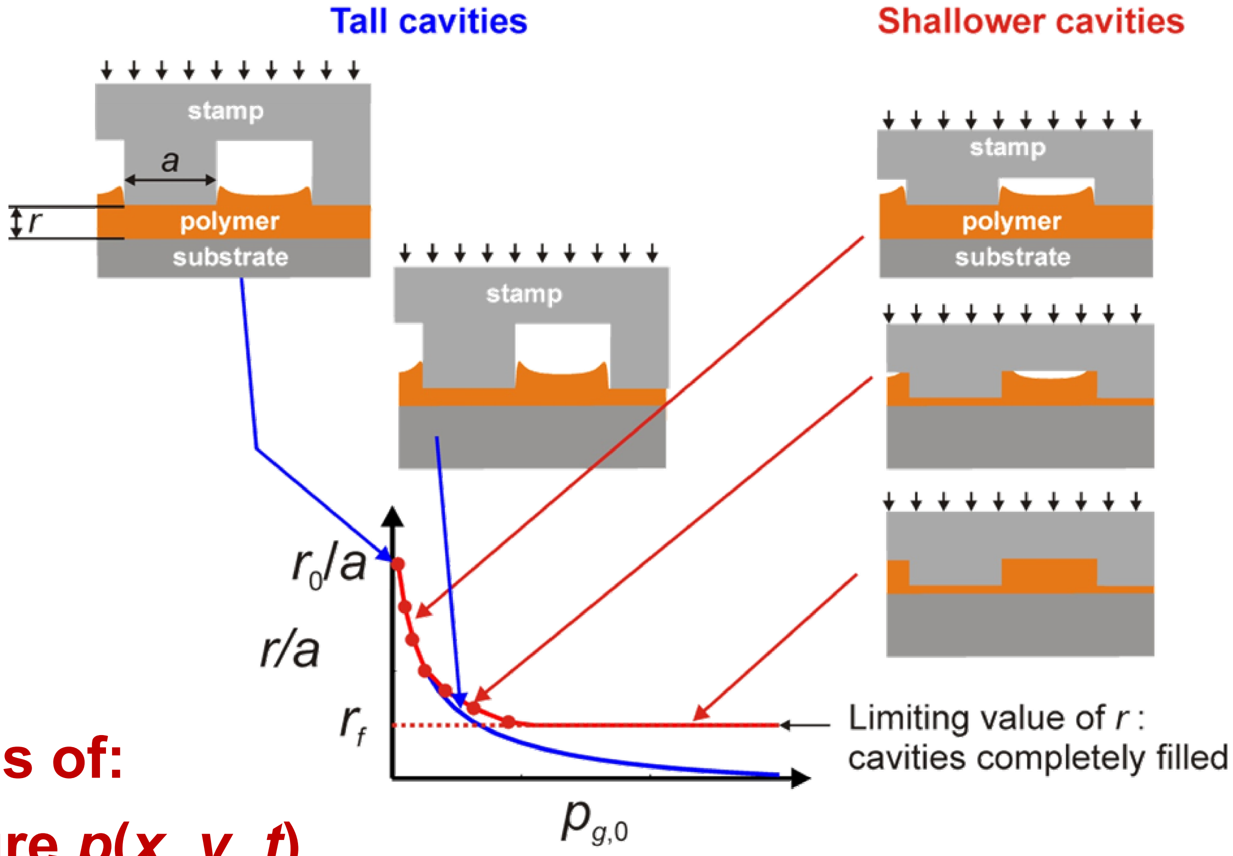






Taylor *et al.*, SPIE 7269 (2009).

Representing layer-thickness reductions

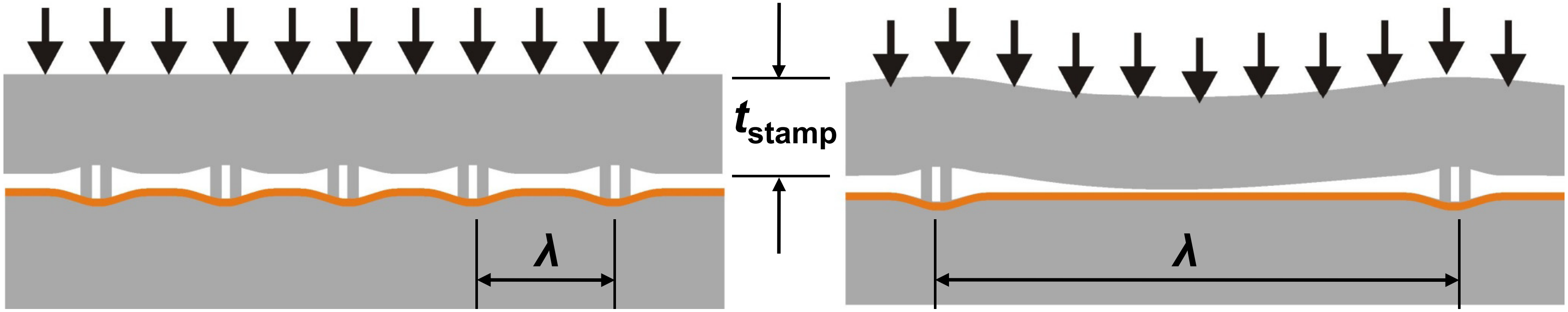


p_g defined in terms of:

- **True pressure $p(x, y, t)$**
- **Material compliance $J(t)$**

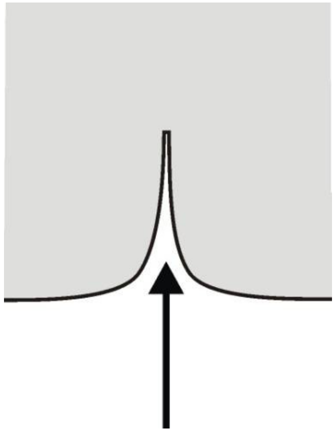
$$p_g\left(x, y, t_h\right) = (1 - \nu^2) \int_0^{t_h} p\left(x, y, t'\right) \frac{\mathrm{d}J\left(t - t'\right)}{\mathrm{d}t'} \mathrm{d}t'$$

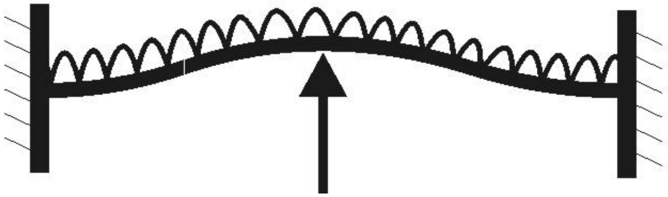
Modeling stamp and substrate deflections


Indentation

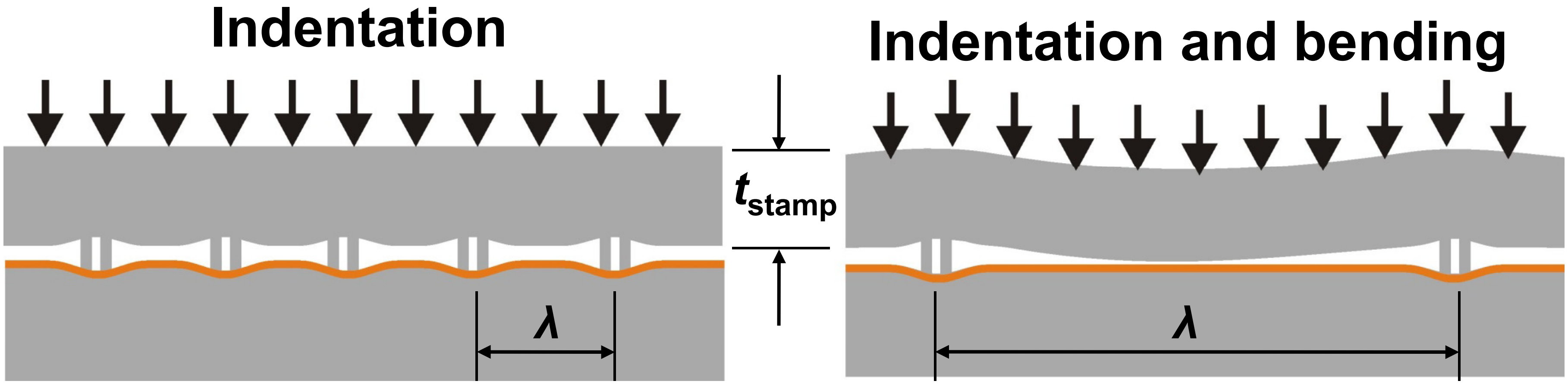
Indentation and bending

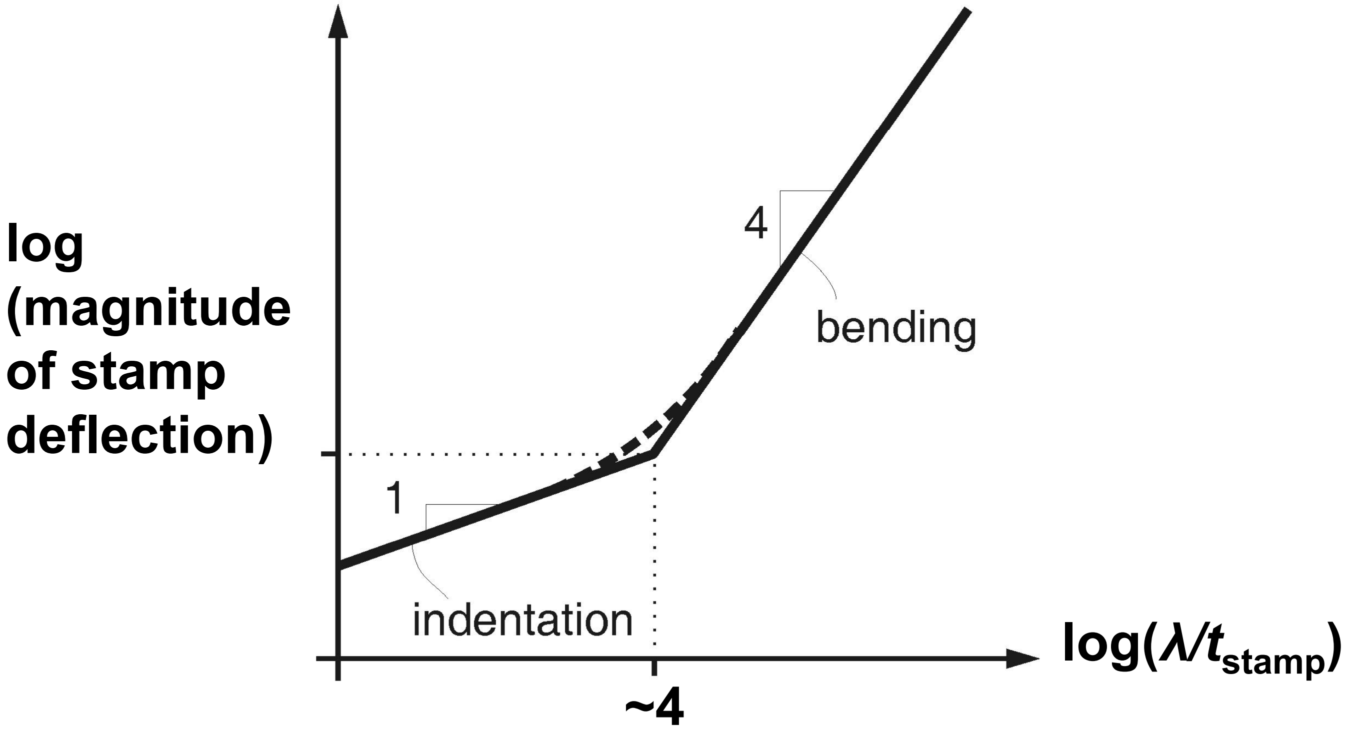
Elastic point-load responses


Indentation


Bending

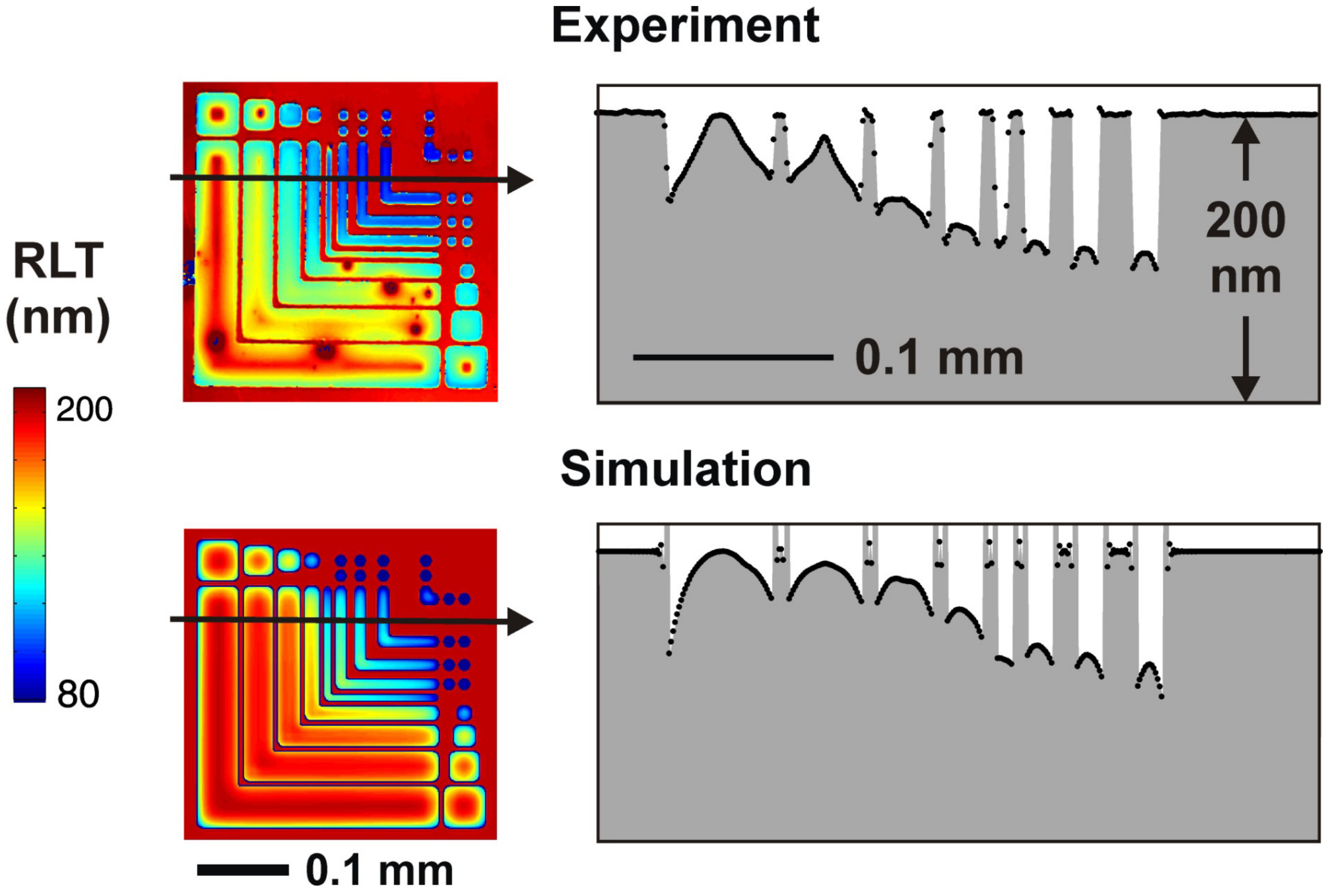
Modeling stamp and substrate deflections





Simulation method: step-up resist compliance

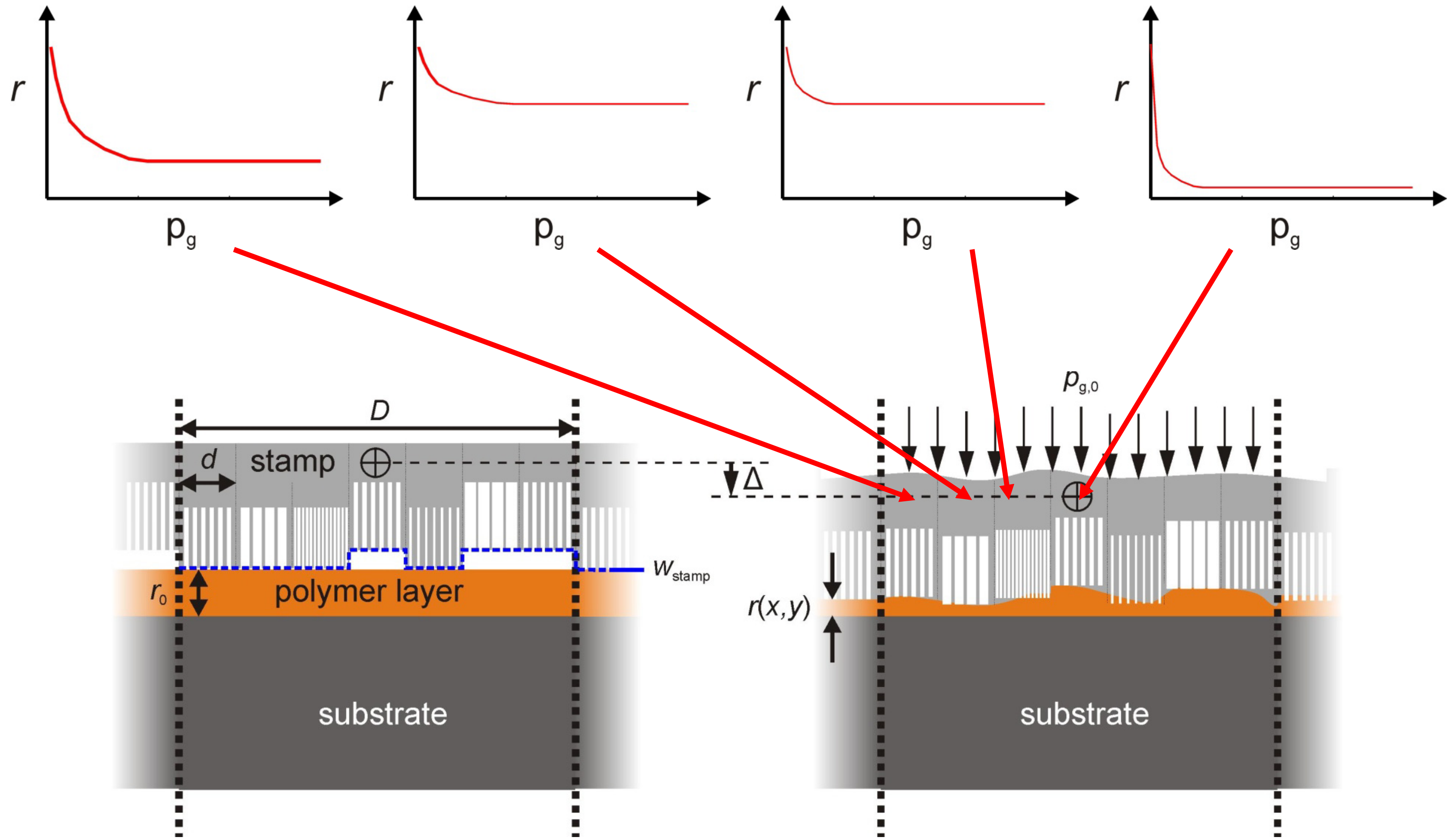
PMMA 495K, *c*. 165 °C, 40 MPa, 1 min


Experiment

Simulation

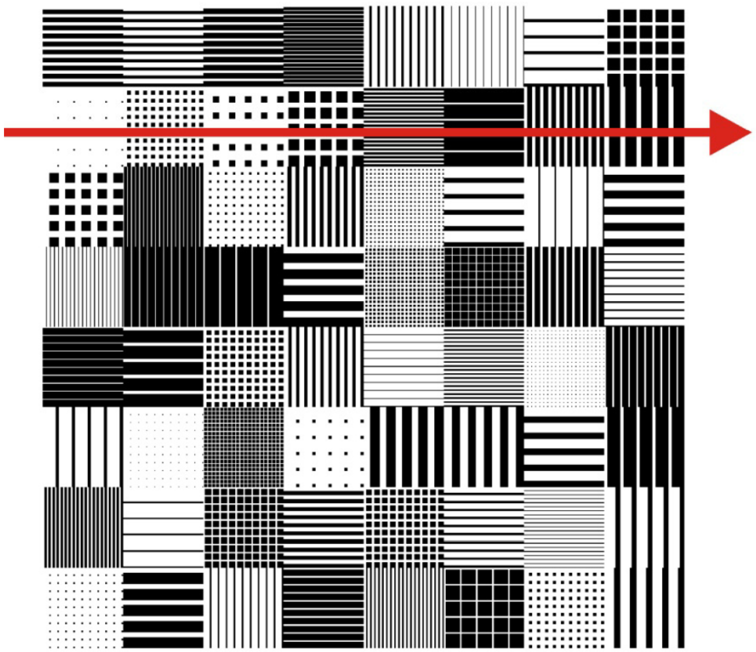
Abstracting a complex pattern

Local relationships between pressure-compliance and RLT:

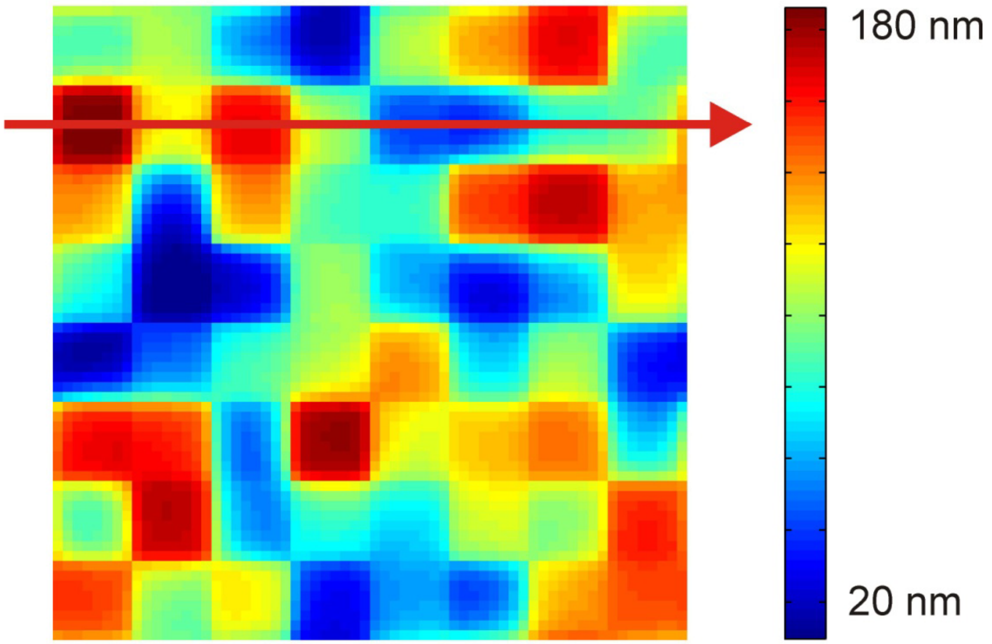


Simulation results: abstracted pattern

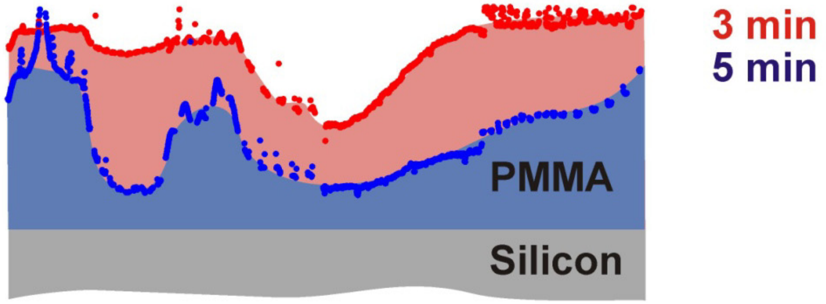
Test-stamp pattern



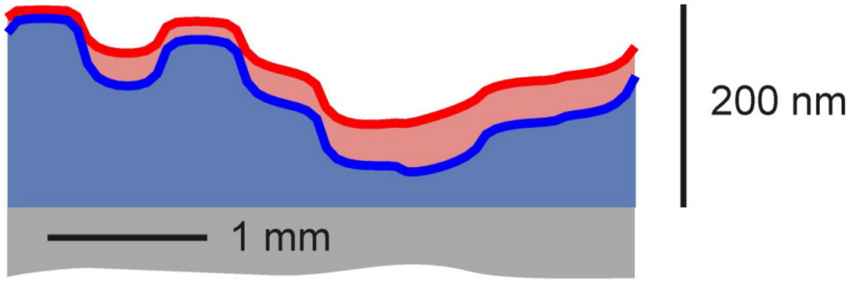
Simulated residual layer thickness



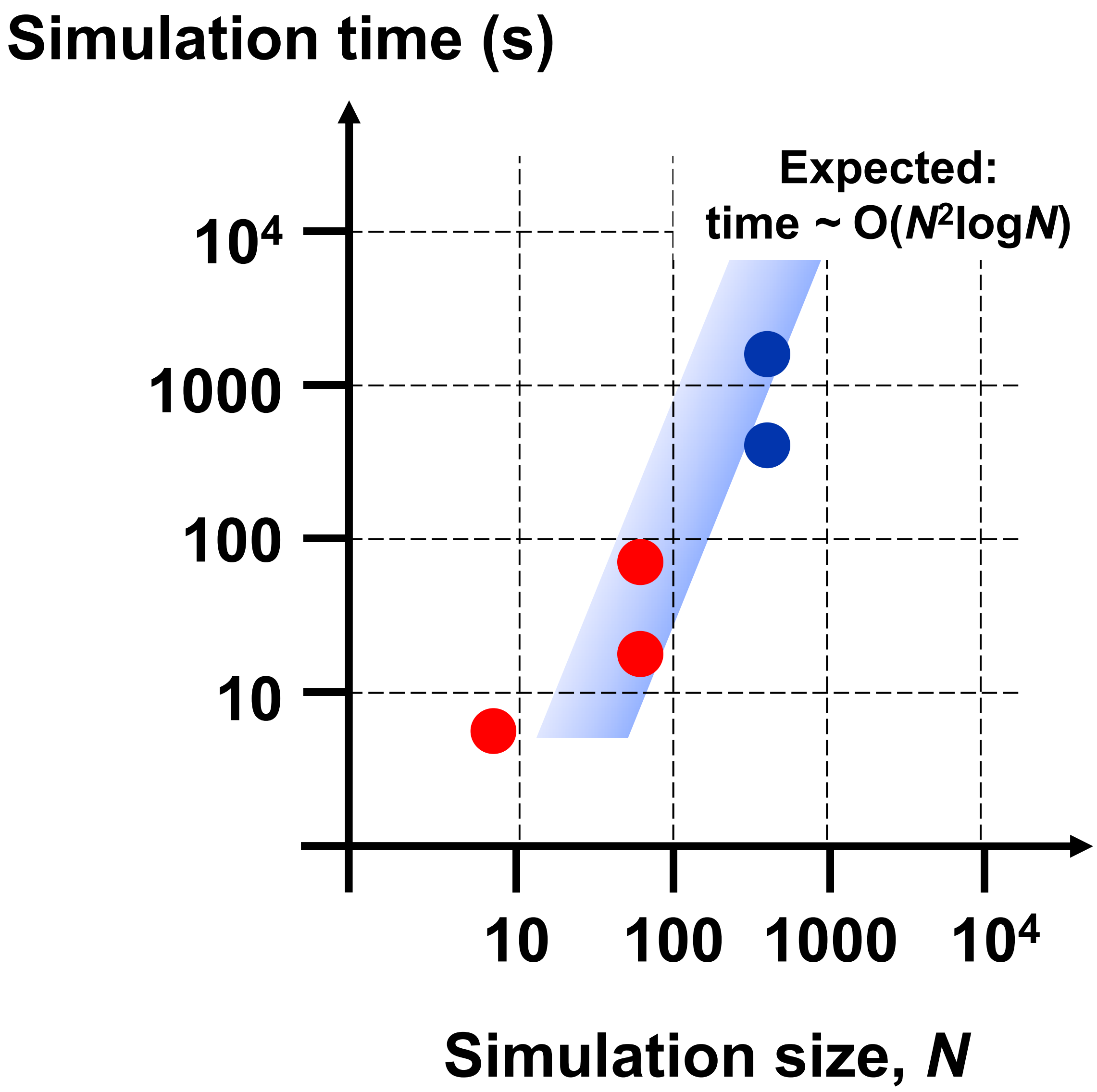
Experimental topography
495K PMMA, 10–15 MPa, 170 °C

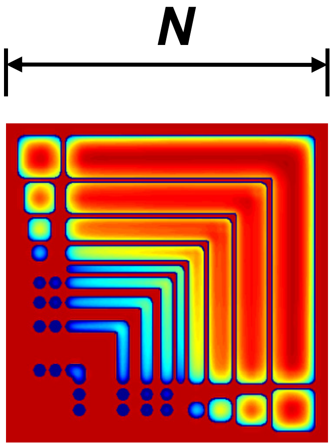


Simulation

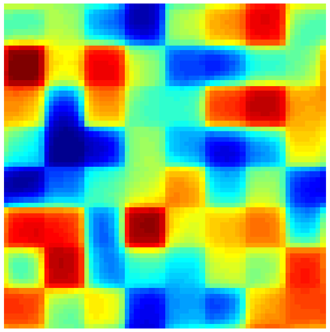


Simulation time





● **Stamp 1**
Feature-scale

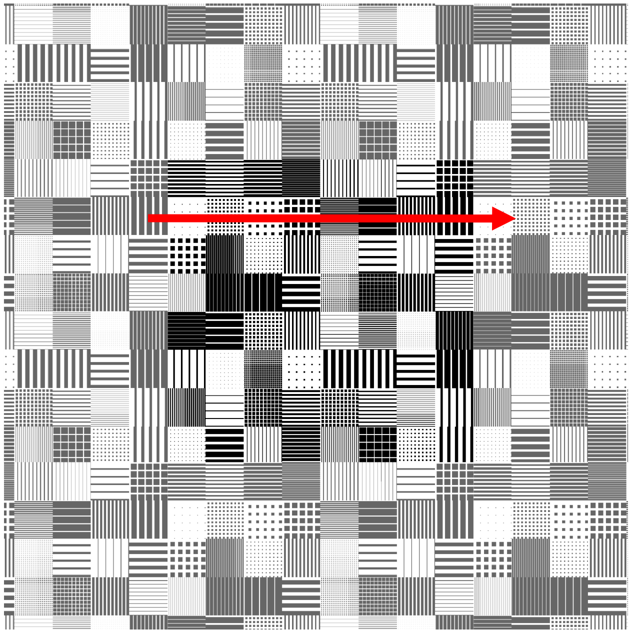


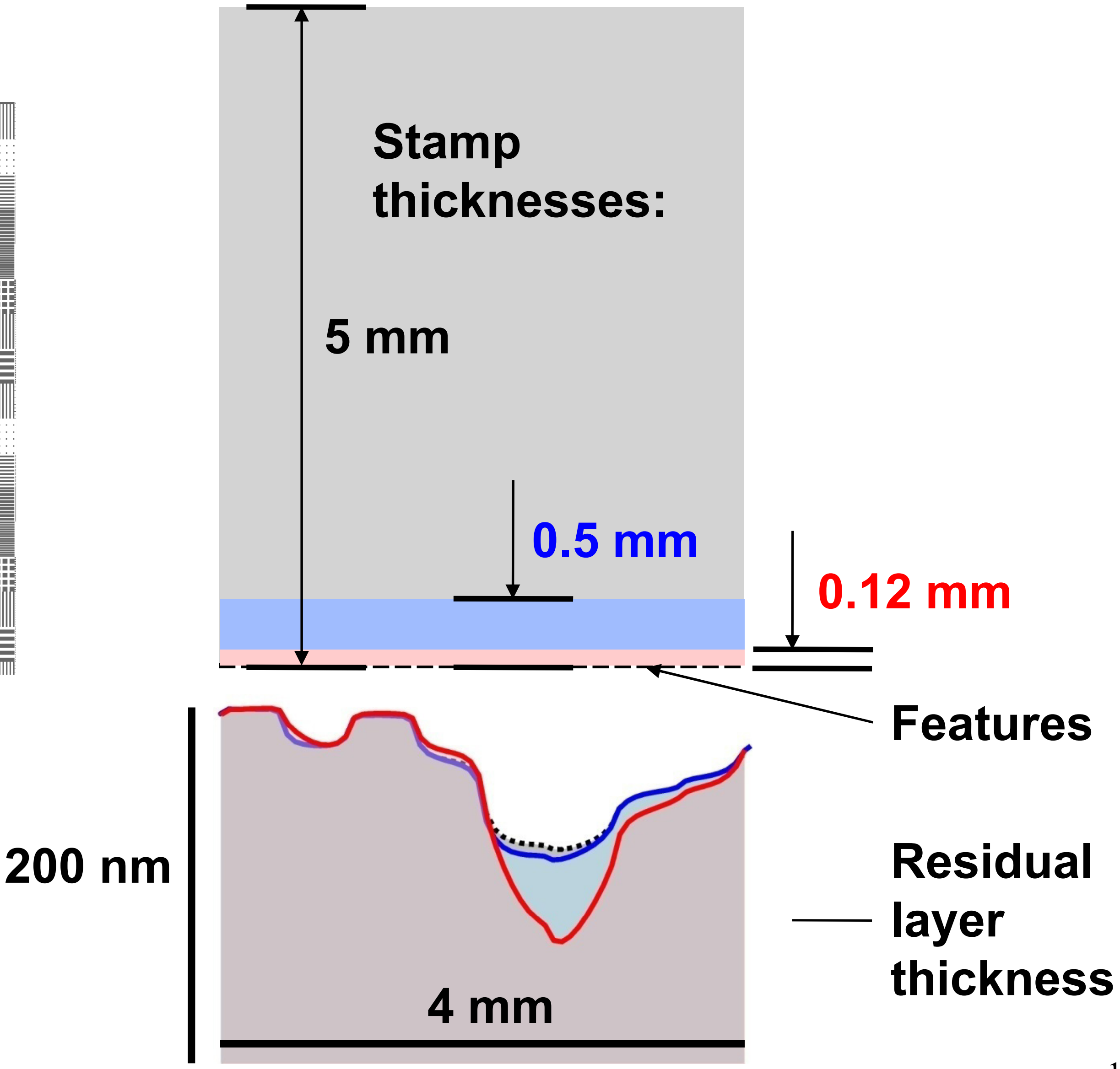
● **Stamp 2**
Abstracted

Strengths of the simulation method

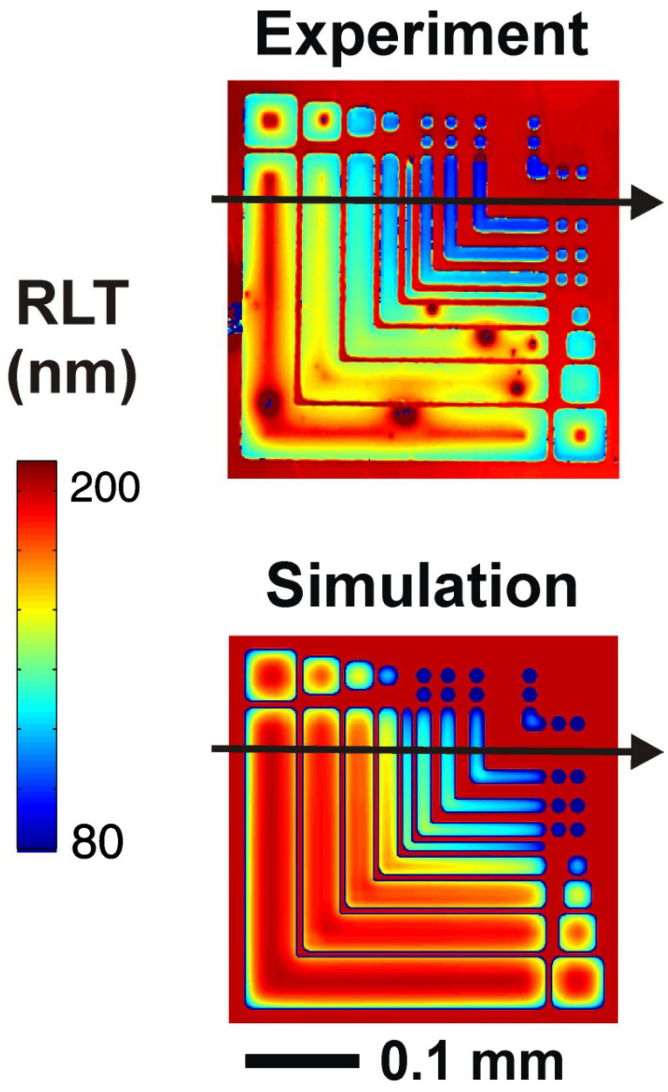
- **A unified simulation approach**
  - Can cope with any layer thickness
  - Can integrate feature sizes ranging over many orders of magnitude
- **Can model any linear viscoelastic material**
- **Speed**
  - At least 1000 times faster than feature-level FEM
- **Implicit periodic boundary conditions are useful**
  - Realistic representation of whole-wafer imprint of many chips
  - Can use edge-padding for non-periodic modeling
- **Suited to quick adaptation for new NIL configurations**
  - Use to explore the use of flexible stamps and substrates
  - Explore the imprinting of non-flat substrates
  - Micro-contact printing; roll-to-roll

Varying stamp’s bending stiffness: simulations





Summary: fast nanoimprint modeling



- **Contributions**
  - Flexible modeling approach
  - Pattern abstraction optional
  - Suited to cell and chip scales
  - 1000+ times faster than FEM
- **Outlook**
  - We will need NIL-aware design checking
  - Can use as an engine for "Mechanical Proximity Correction"

Acknowledgements

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  - The Singapore-MIT Alliance
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