Towards nanoimprint lithography-aware layout design checking

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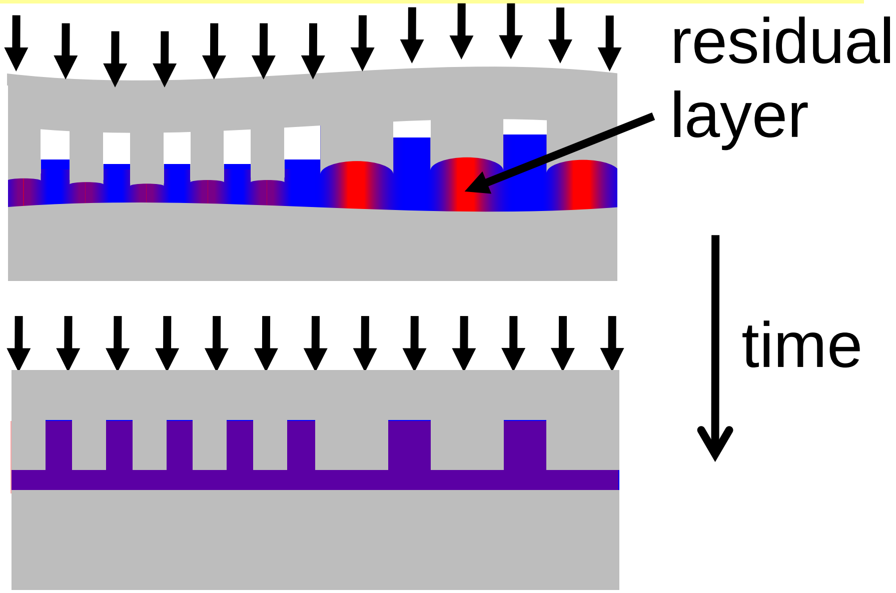
THE IET AWARDS 2009
INNOVATION WINNER

Nanoimprint is the mechanical patterning of resist spun or sprayed on to a wafer

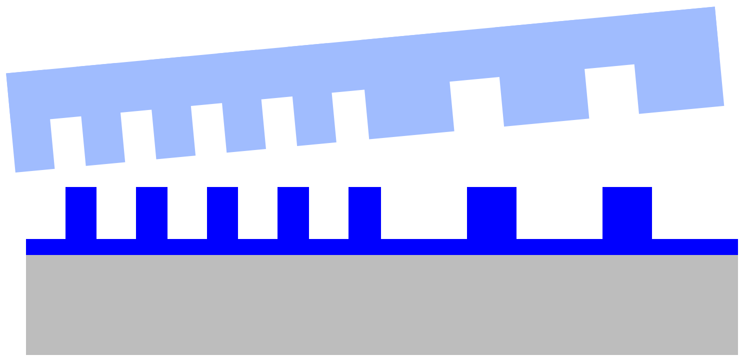
Spun-on resist



- Resist viscosity ≥ 10^3 Pa.s
- Applied pressures ~ 5 MPa
- Thermoplastic or UV-curing
- Viscous resist squeezing
- Elastic stamp deflections

S.Y. Chou *et al., Appl. Phys. Lett.* vol. 67 pp. 3114-3116, 1995
S. Fujimori, Jpn. J. Appl. Phys. vol. 48 p. 06FH01, 2009

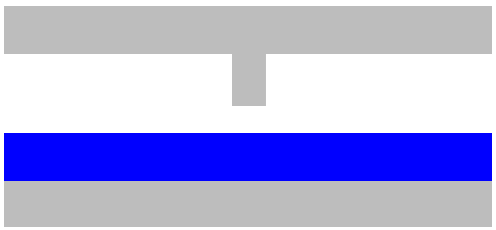
Droplet-dispensed resist

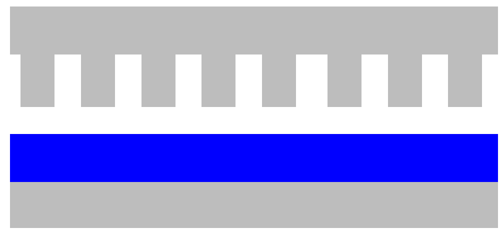


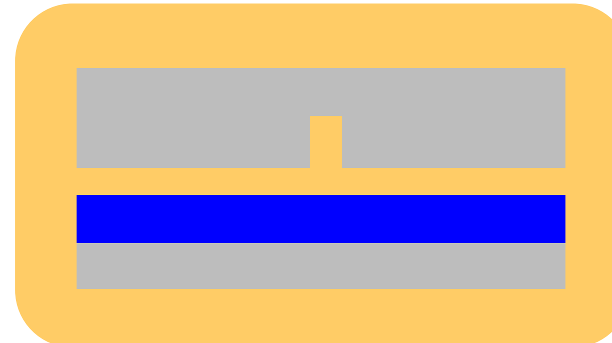
- Resist viscosity < 0.1 Pa.s
- Applied pressures ~ 5 kPa
- Droplets tailored to pattern
- Key figure of merit: filling time
- Gas trapping and dissolution

M. Colburn *et al*., SPIE 3676, pt.1-2, 379-89, 1999
www.molecularimprints.com

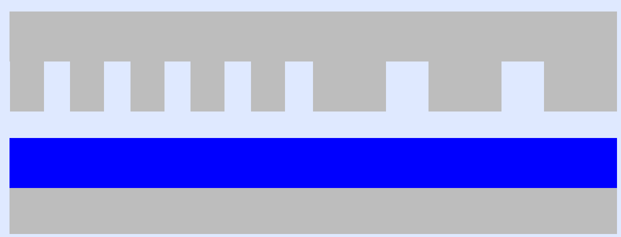
Nanoimprinting of spun-on layers exhibits pattern dependencies





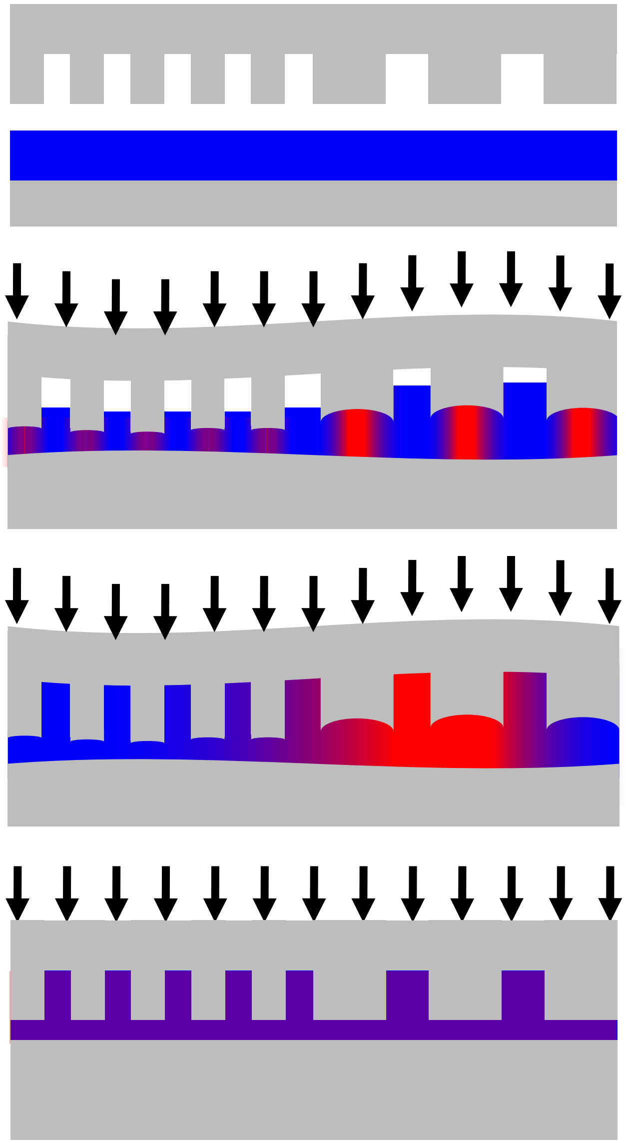


Not realistic in semiconductors



Pattern density already constrained to a modest range (typ. 40-60%)

Nanoimprinting of spun-on layers exhibits pattern dependencies

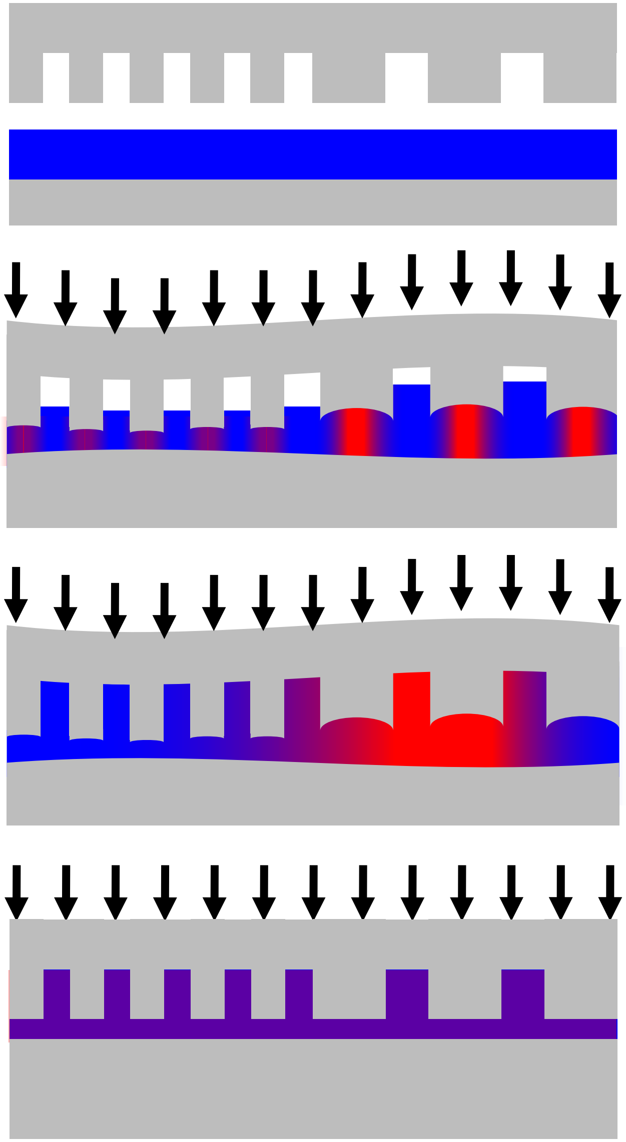


Two relevant timescales for pattern formation:

Local cavity filling

Residual layer thickness (RLT) homogenization

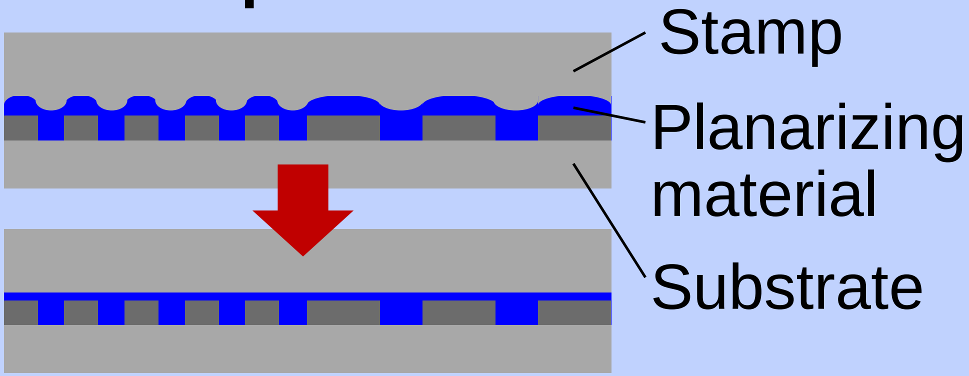
Nanoimprinting of spun-on layers exhibits pattern dependencies



Objective for nanoimprint-friendly design:

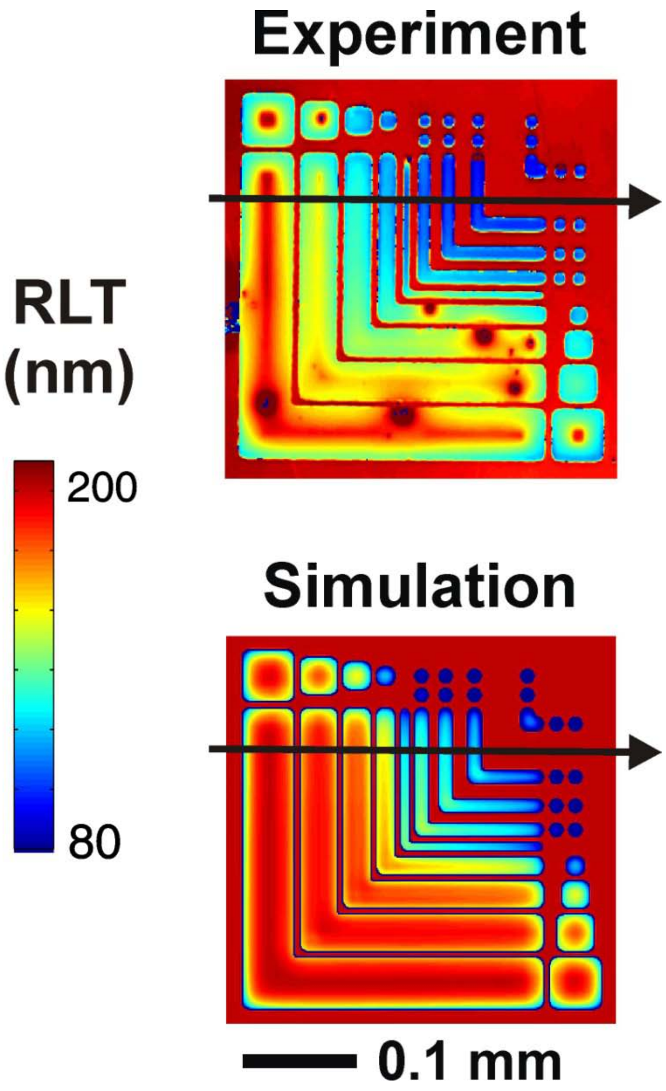
Limit time to bring residual layer thickness variation within spec.

NIL for planarization



Similarly, limit time to bring NIL-planarized surface within spec.

Nanoimprint modeling and simulation needs



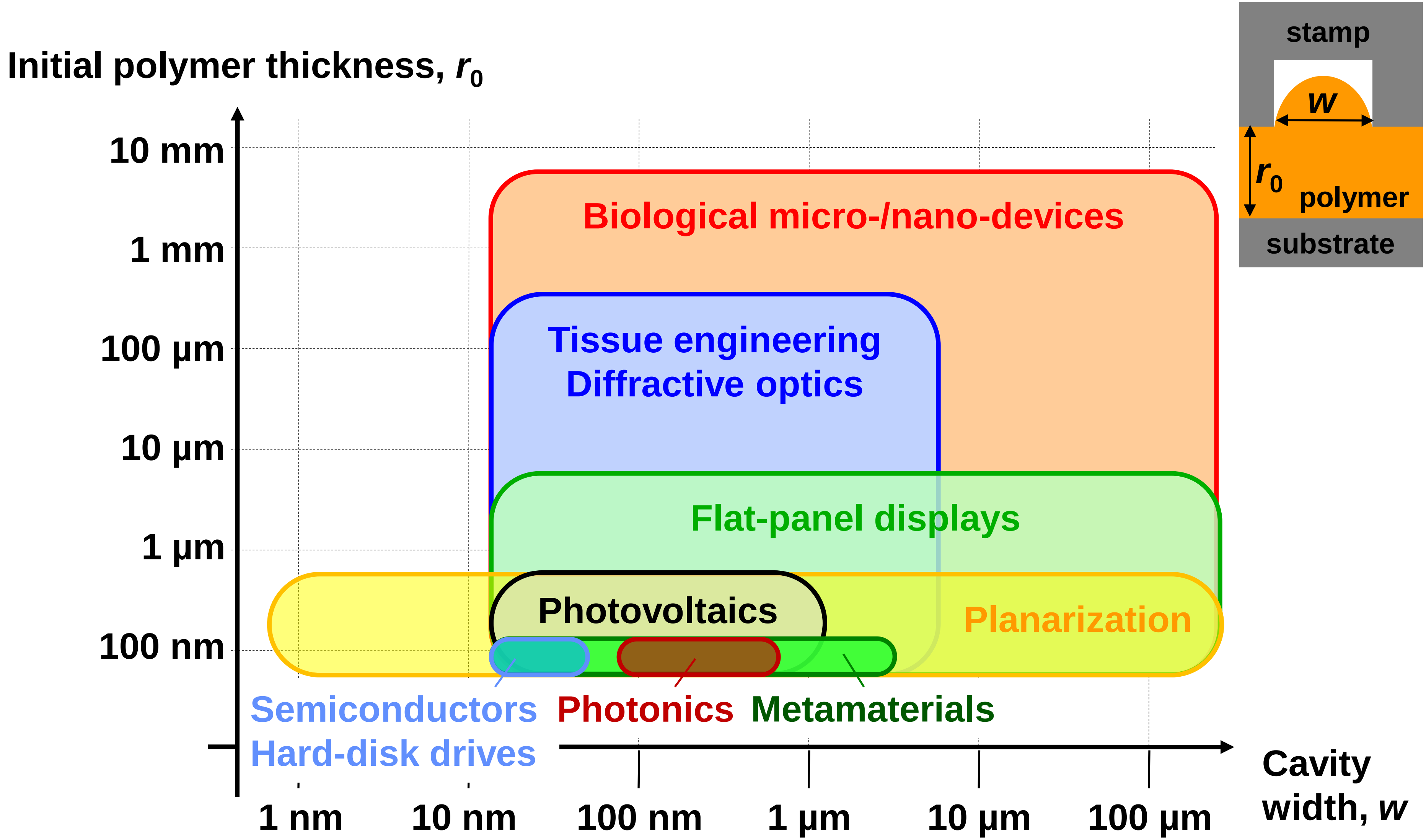
- **Cell-level**
  - Hundreds of features
  - Guide iterative layout design
  - Desktop processing in minutes
- **Chip-level**
  - Many millions of features
  - Pre-fabrication check: overnight?
  - Guide process selection
- **Need for flexibility**
  - Rapid innovation in resist and stamp materials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

Nanoimprint compared to photolithography modeling

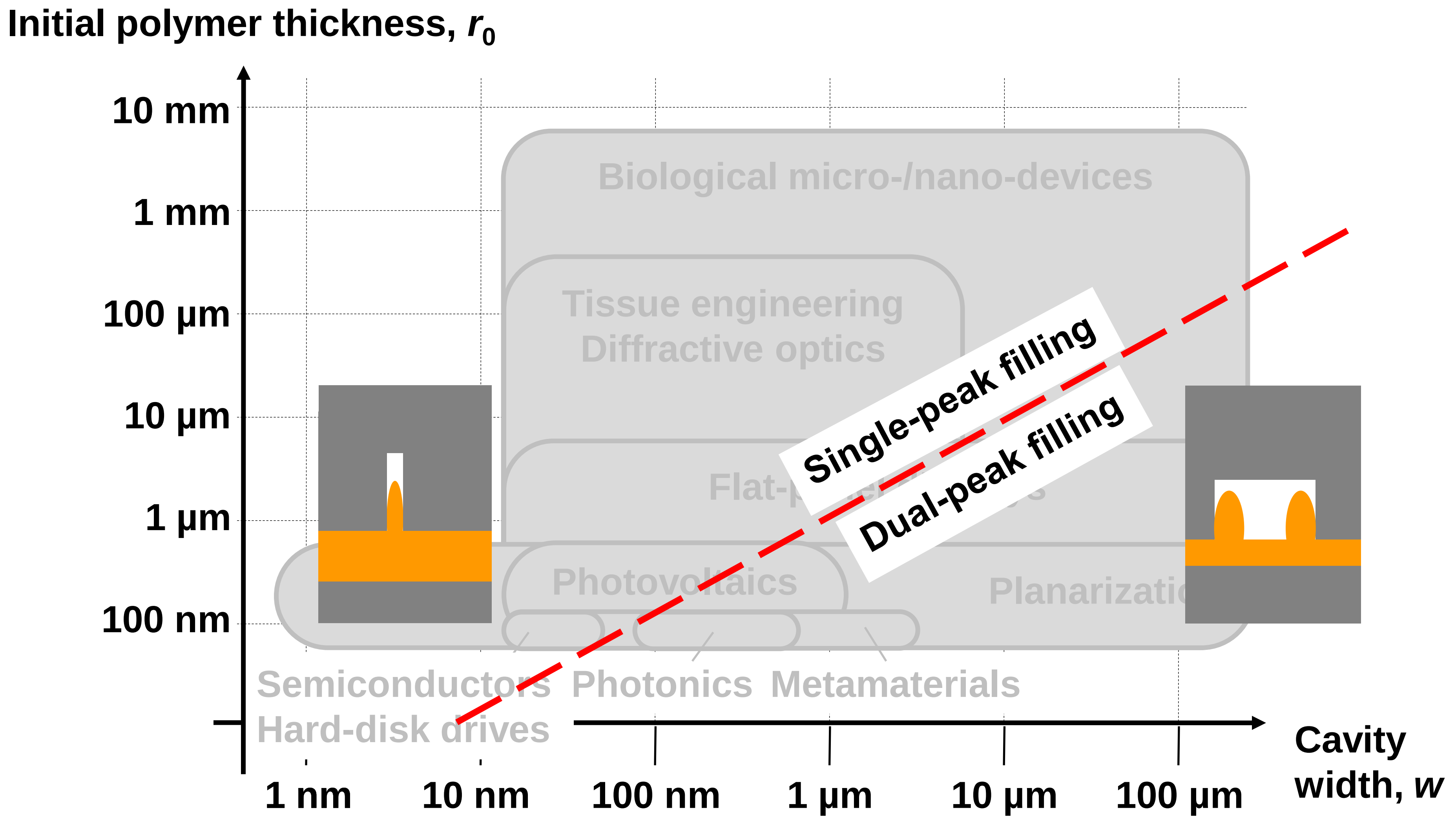
	Photolithography	Nanoimprint
Feature-scale	**PROLITH; "TCAD"**	**Hirai[1]; Rowland[2]; Scheer[3]; Reddy[4]**
Chip-scale	**OPC software**	**Mendels/Zaitsev[5];** ***and this work***

[1] Y. Hirai *et al.*, *Microelectronic Eng*. vol. 85 p. 842, 2008.
[2] H.D. Rowland and W.P. King, *J Micromech Microeng*, vol. 15, p. 1625, 2004.
[3] H-C. Scheer *et al.*, *Microelectronic Eng.*, vol. 84, p. 949, 2007.
[4] S. Reddy *et al.*, *Phys. Fluids*, vol. 17, p. 122104, 2005.
[5] N. Kehagias *et al.*, *Microelectronic Eng.*, vol. 85, p. 846, 2008.

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

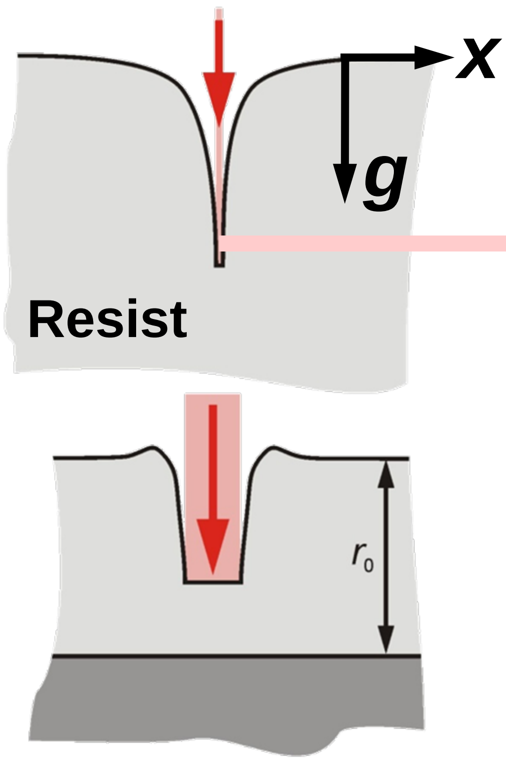


We need a unified simulation approach for micro- and nano-embossing/imprinting

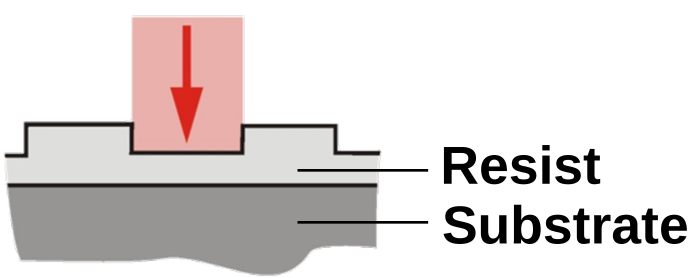


Key: model impulse response *g*(*x*,*y*,*t*) of resist layer

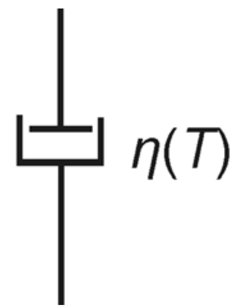
Model in space:



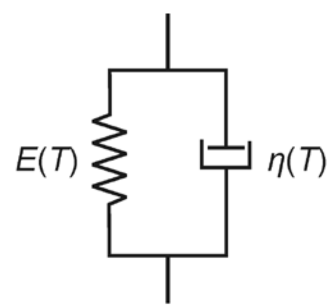
Mechanical impulse applied uniformly over small region at time *t* = 0



Model in time:



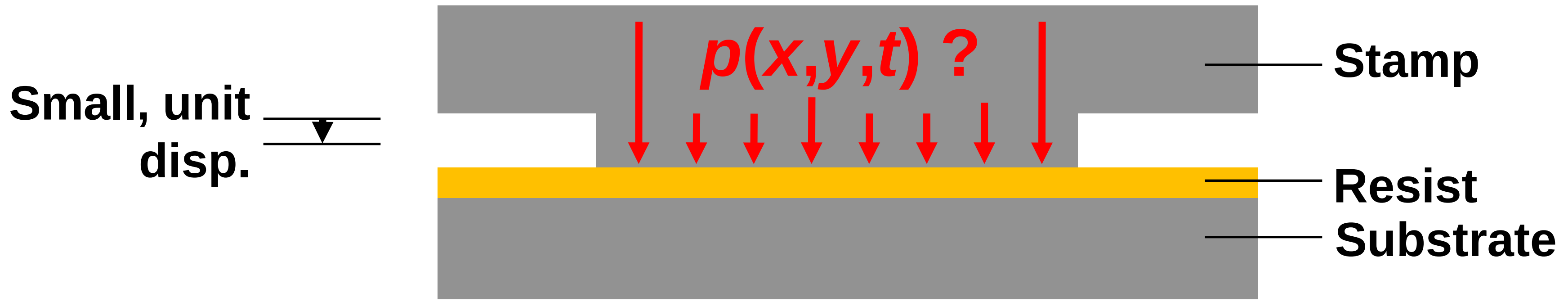
Newtonian: impulse response constant in time for *t* > 0



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



Time increment

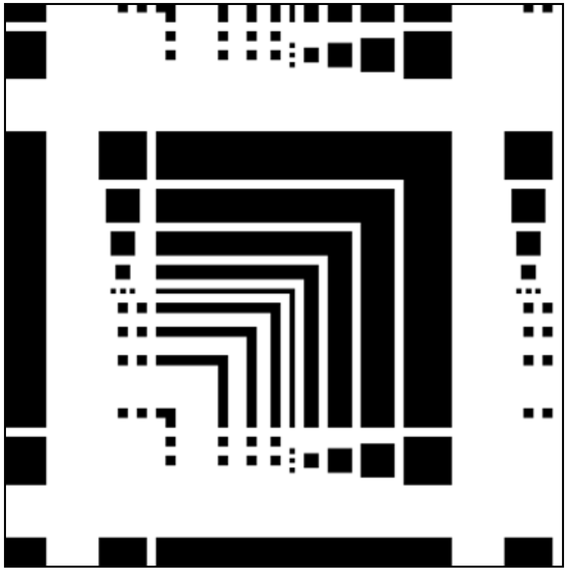
$$\left[p(x,y,t) * g(x,y,t)\right]\Delta t = \mathbf{1}$$

Pressure **?** — Impulse response — Unit displacement in contact region

Contact pressure distributions can be found for arbitrary stamp geometries

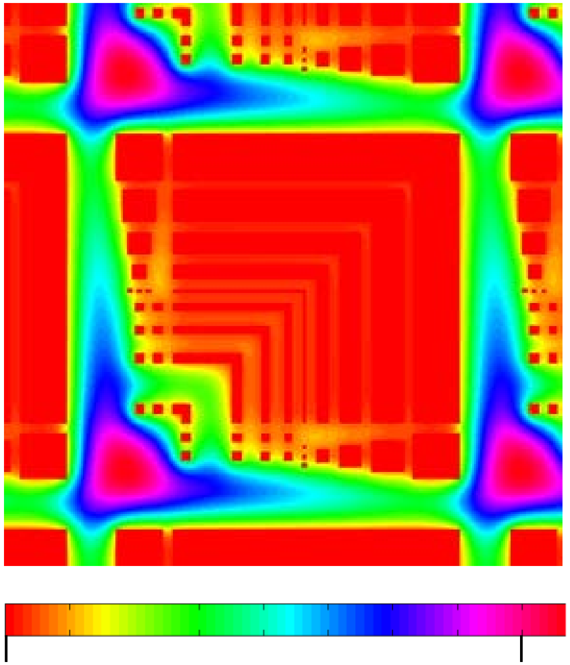
2.3 µm-thick polysulfone film embossed at 205 °C under 30 MPa for 2 mins

Stamp design



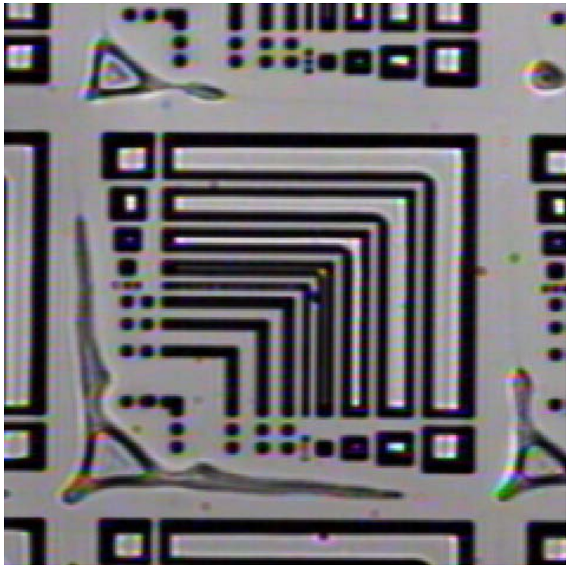
■ **Cavity**

Simulated pressure



0 **160 MPa**

Optical micrograph

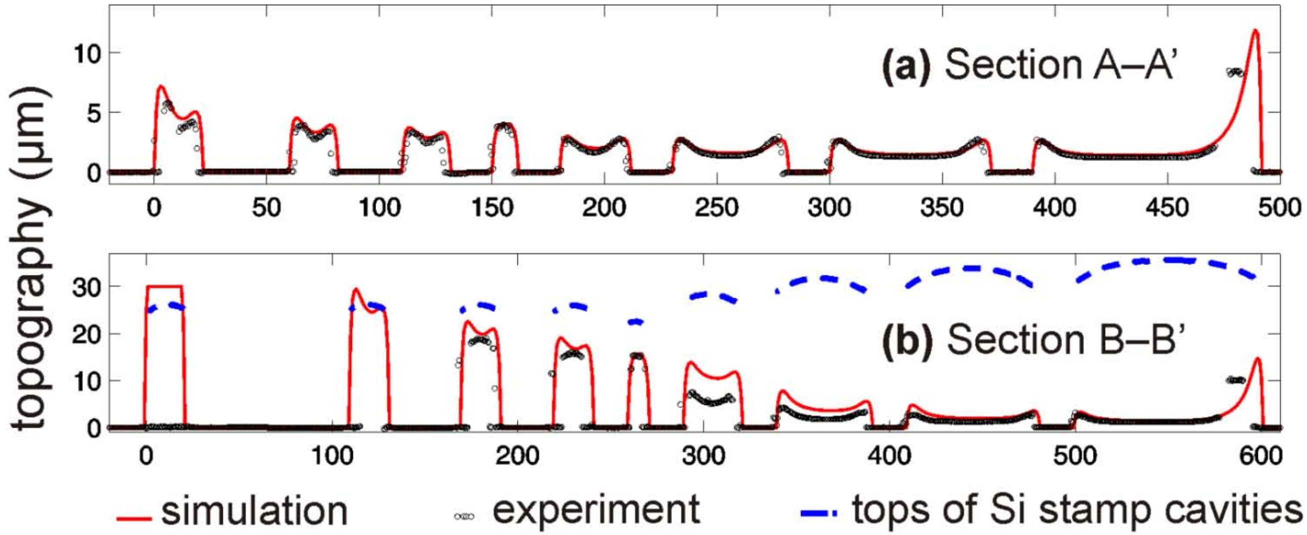


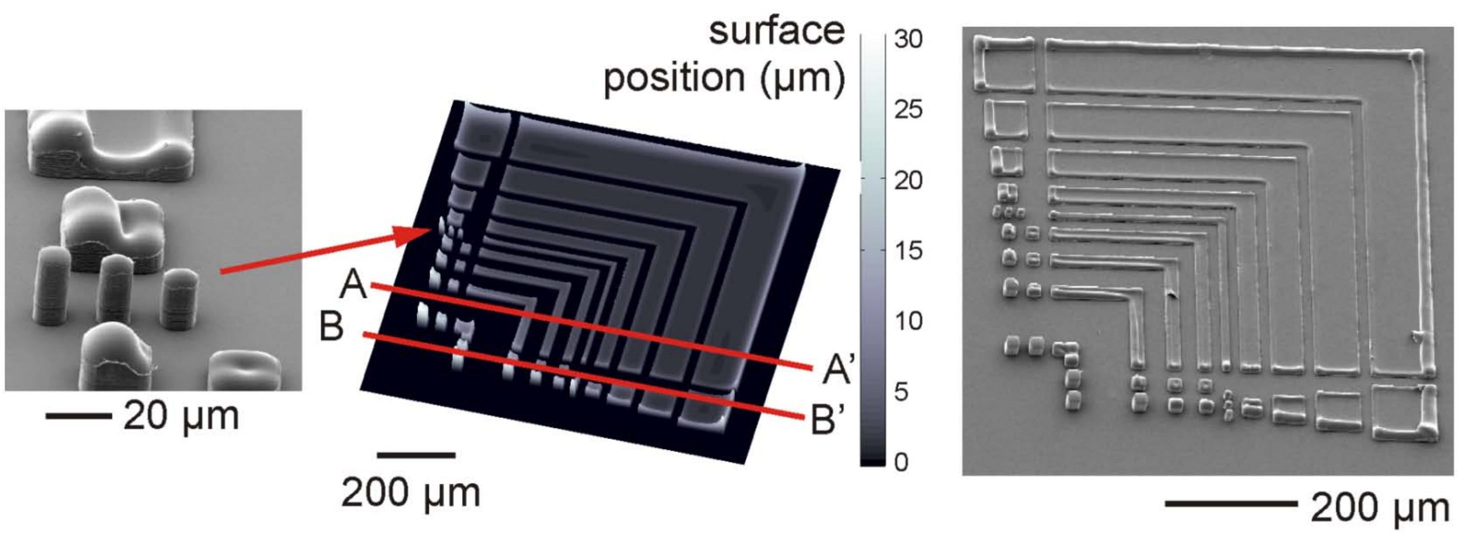
— 200 µm

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

Successful modeling of polysulfone imprint

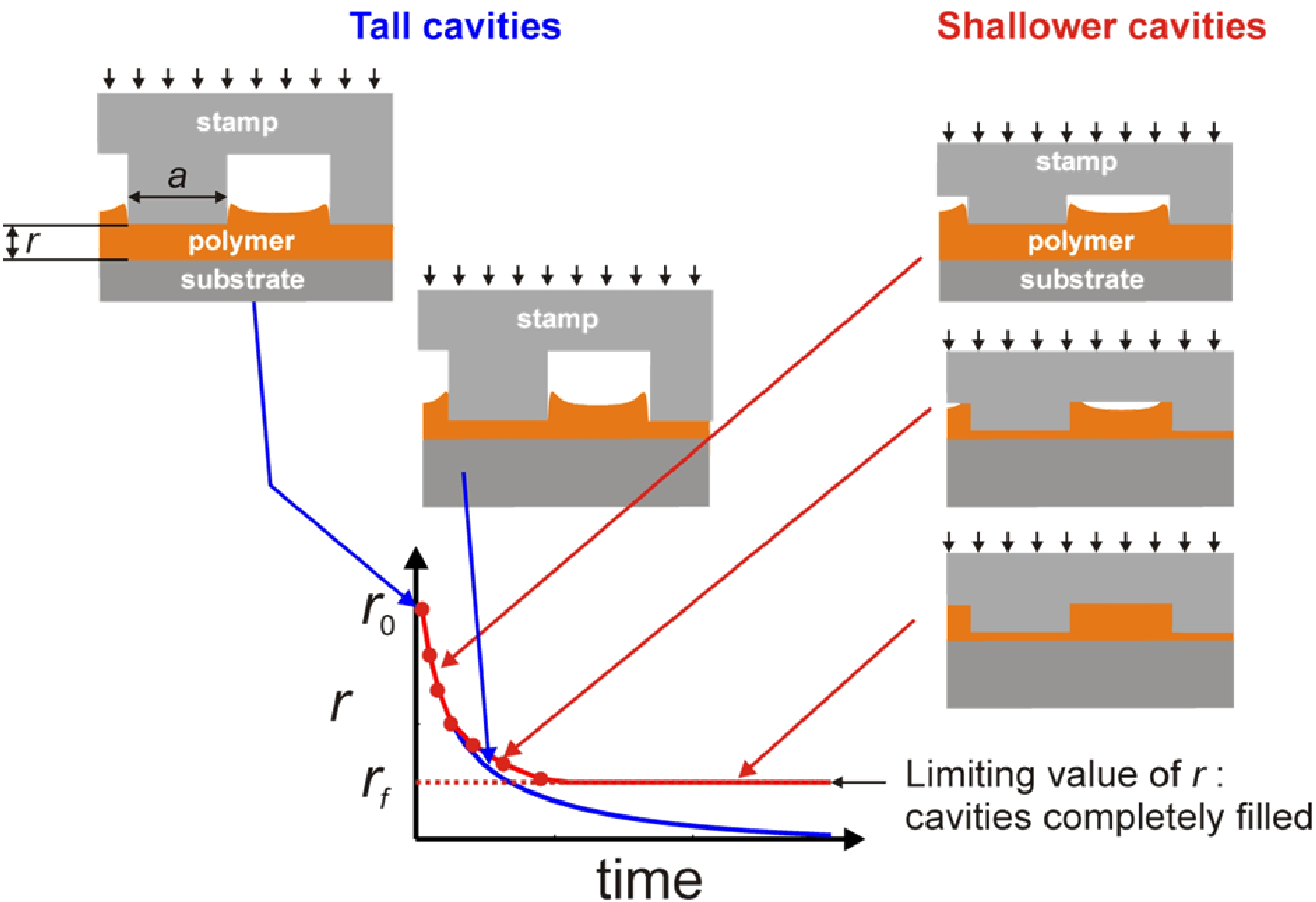
2.3 µm-thick polysulfone film embossed at 205 °C under 30 MPa for 2 mins



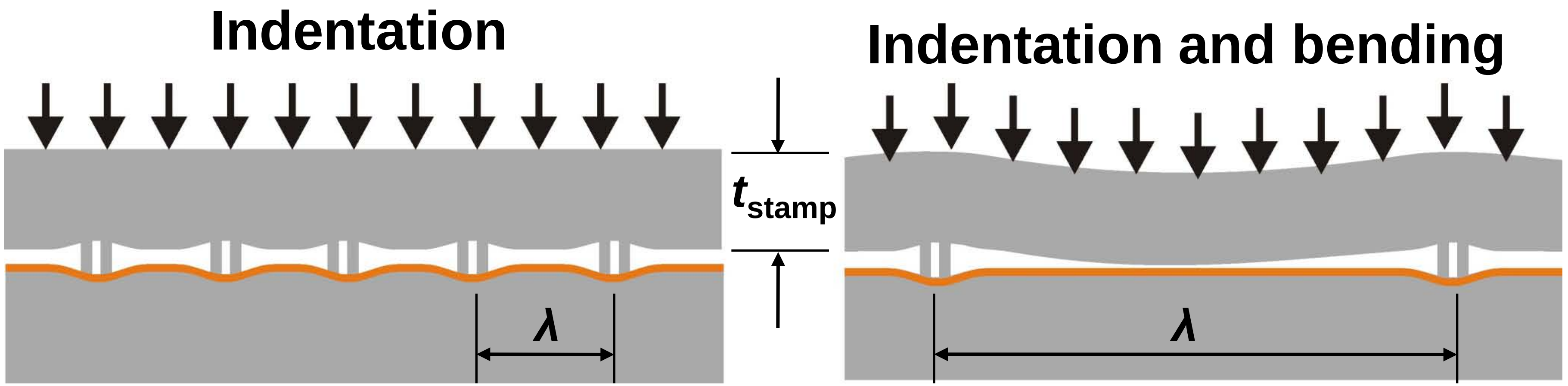


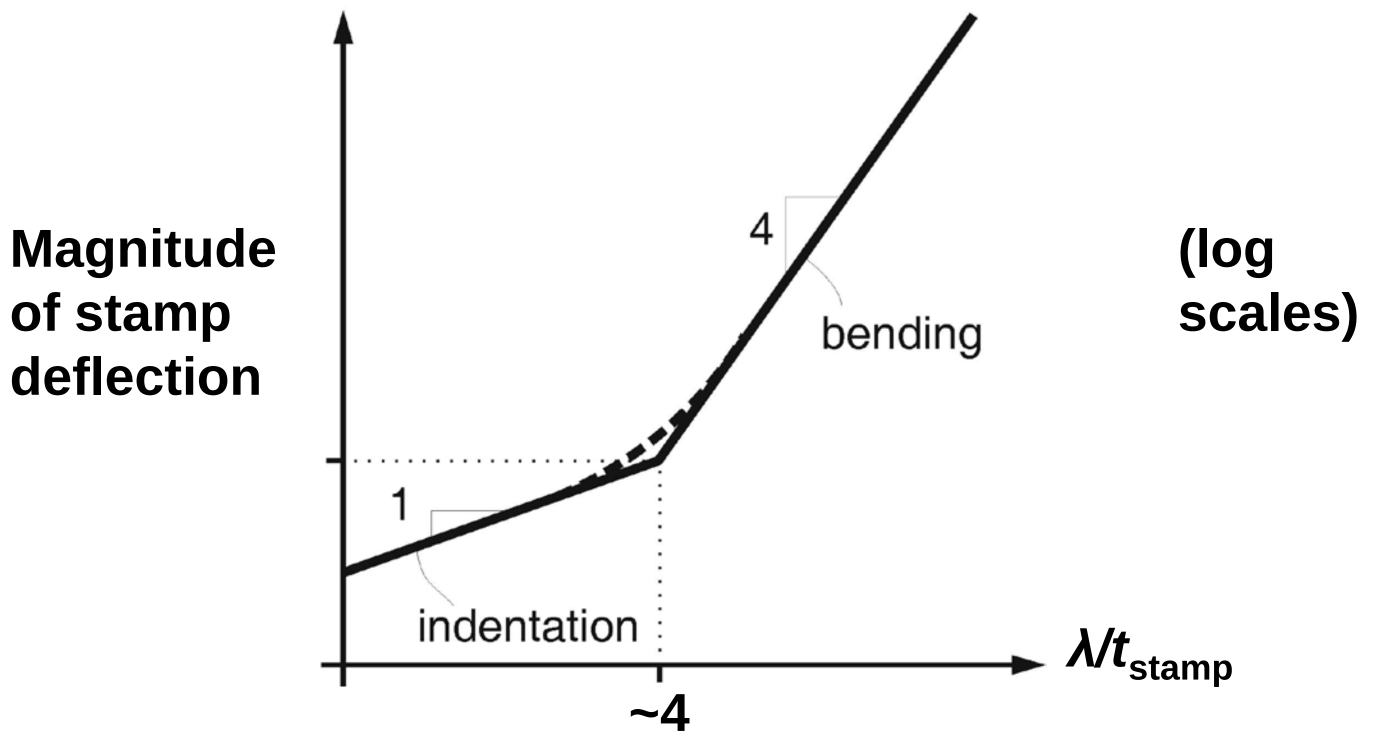
Taylor *et al.*, SPIE 7269 (2009).

Representing layer-thickness reductions



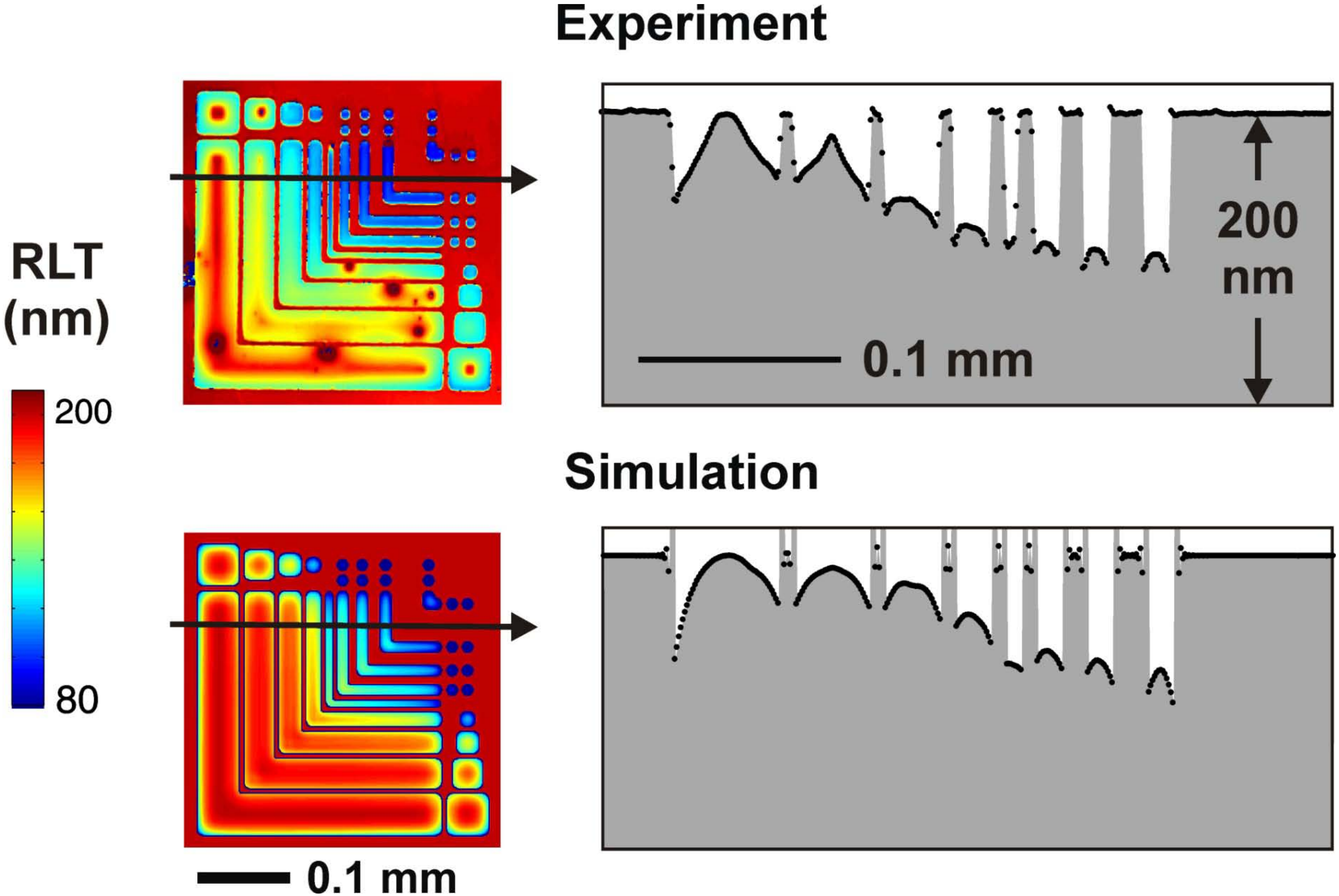
Modeling stamp and substrate deflections





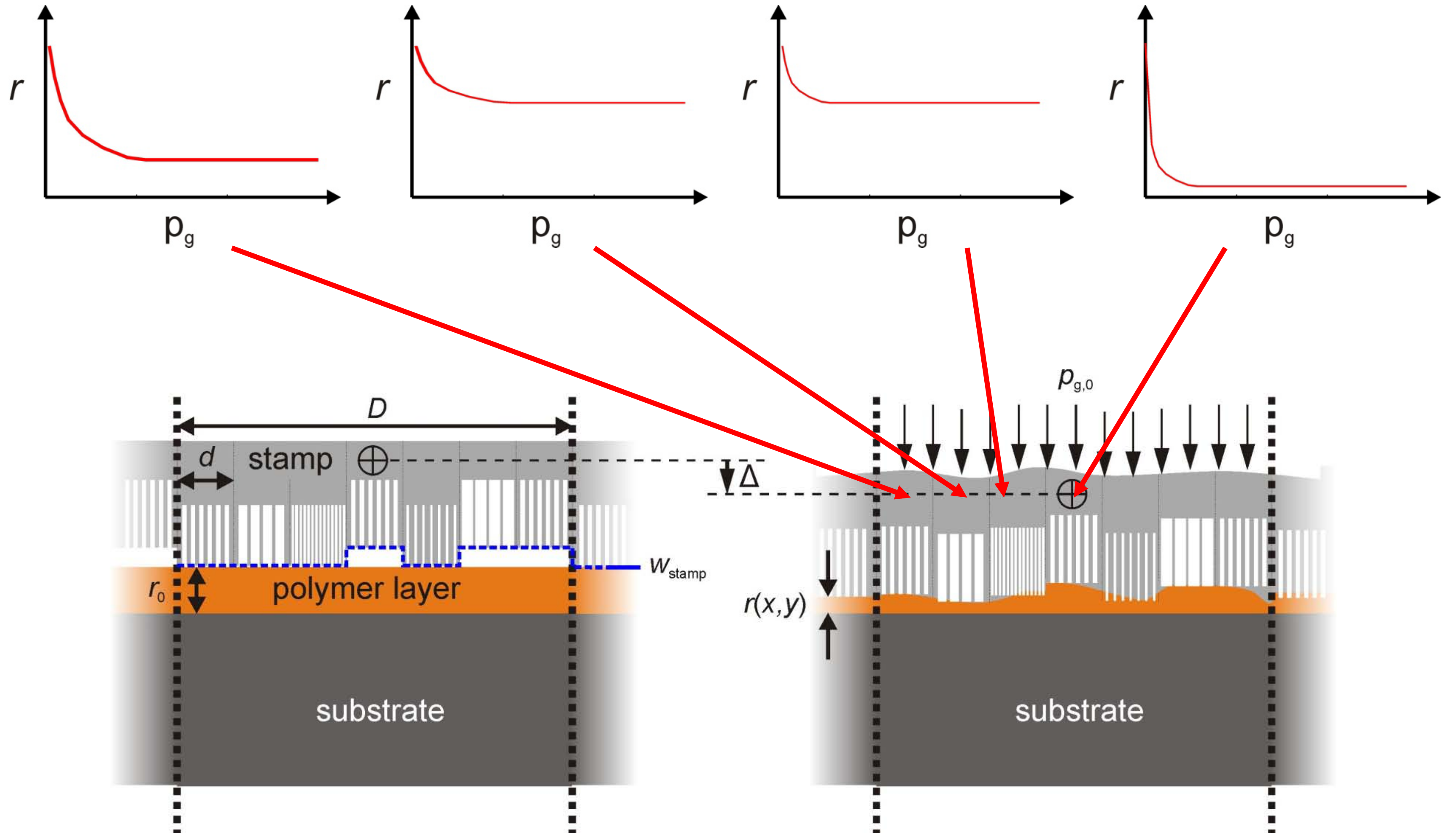
Simulation method: step-up resist compliance

PMMA 495K, *c*. 165 °C, 40 MPa, 1 min

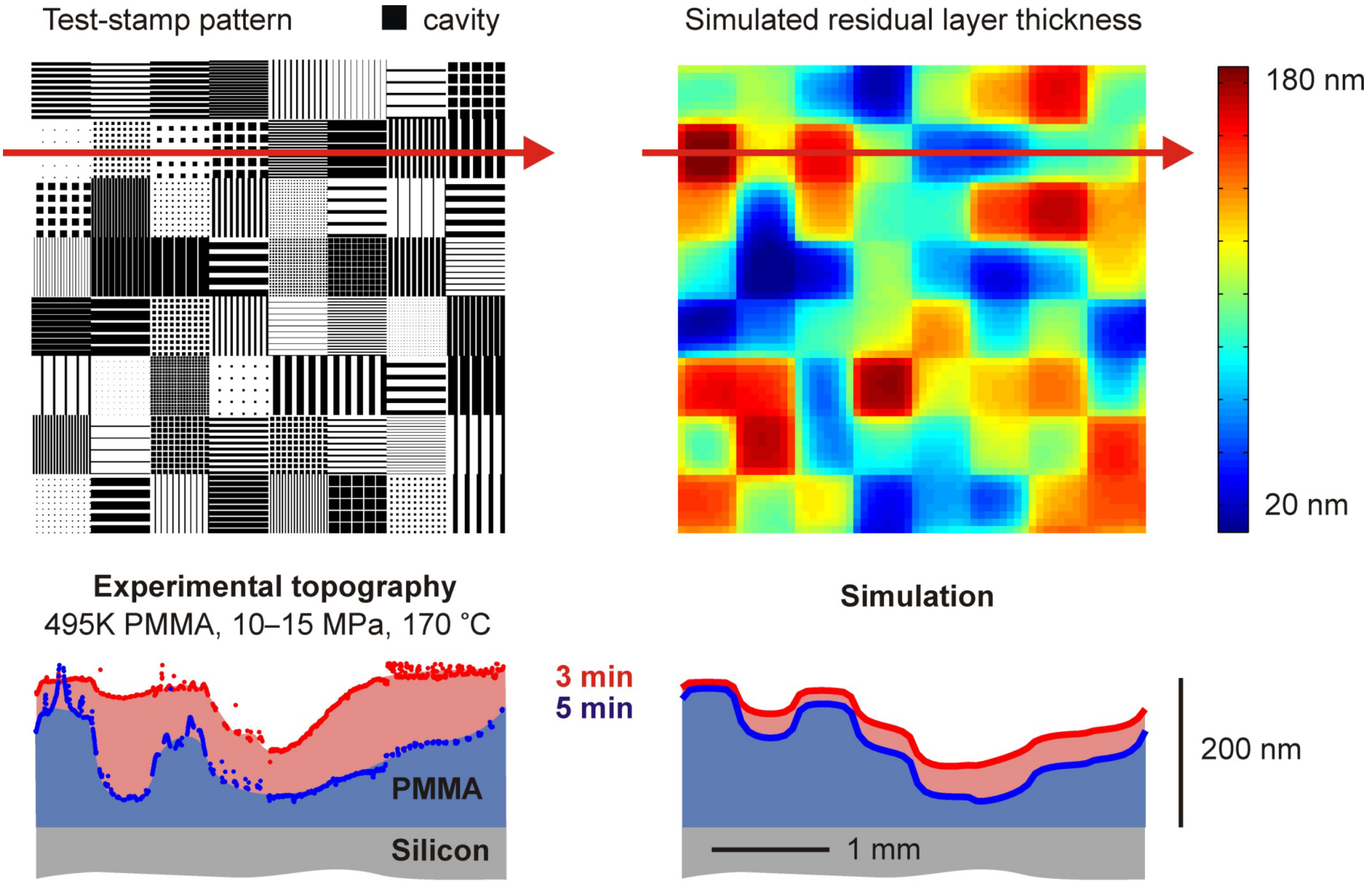


Abstracting a complex pattern

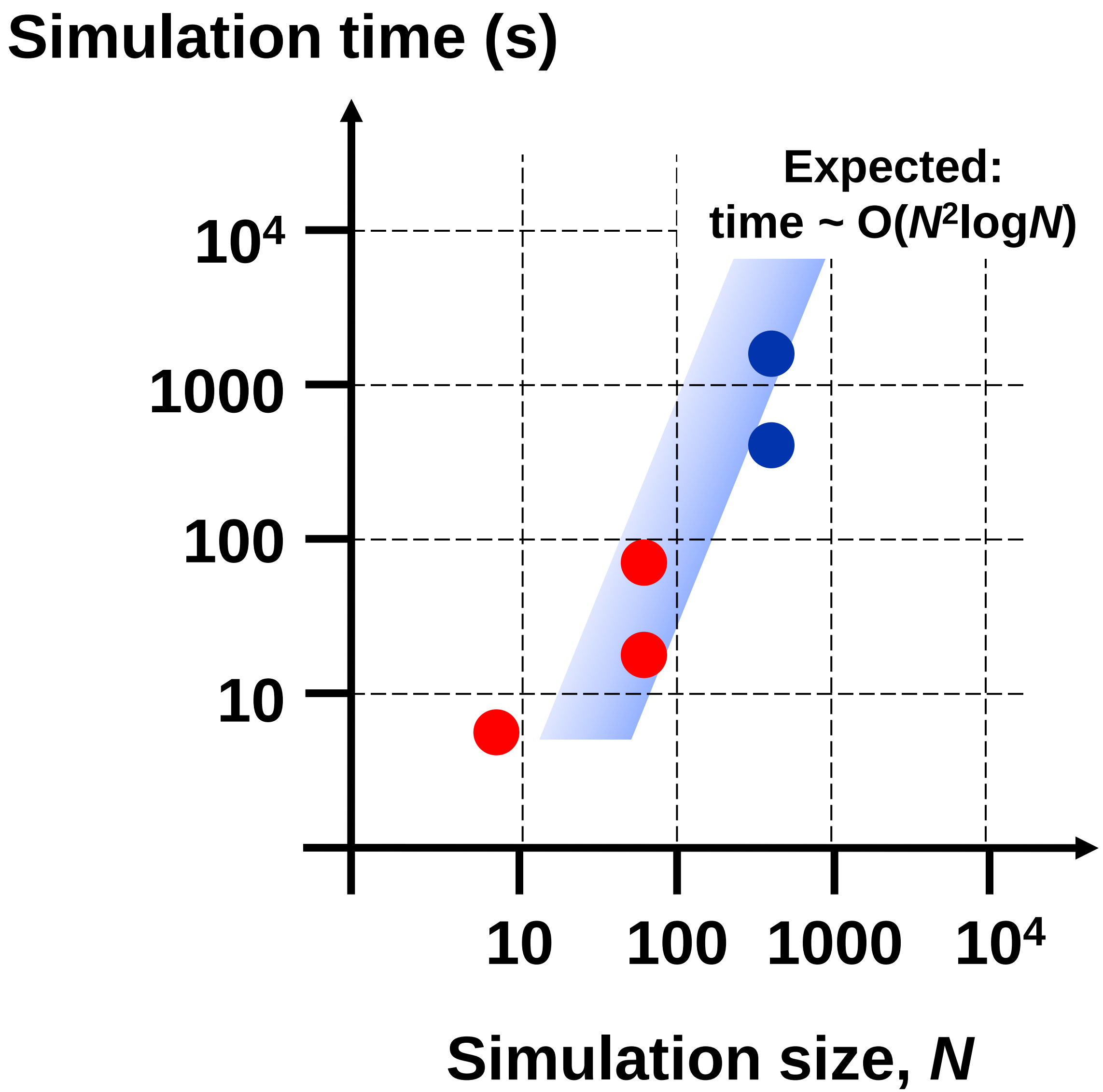
Local relationships between pressure-compliance and RLT:

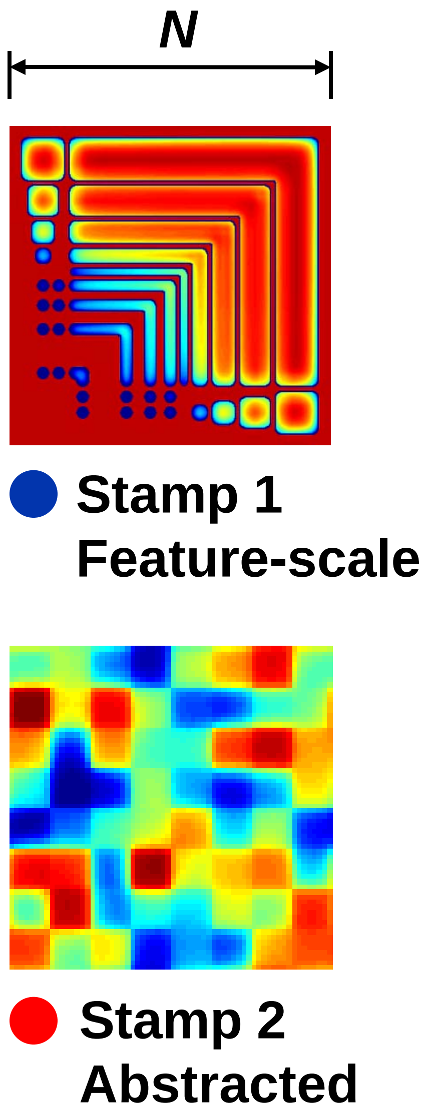


Simulation results: abstracted pattern



Simulation time



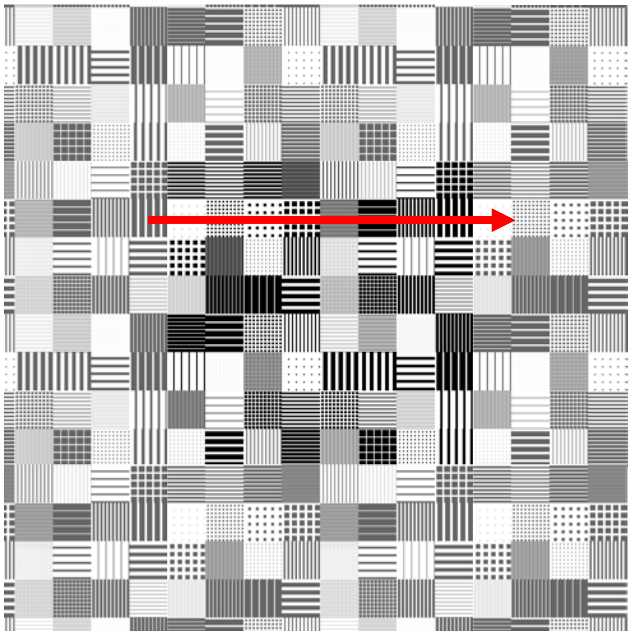


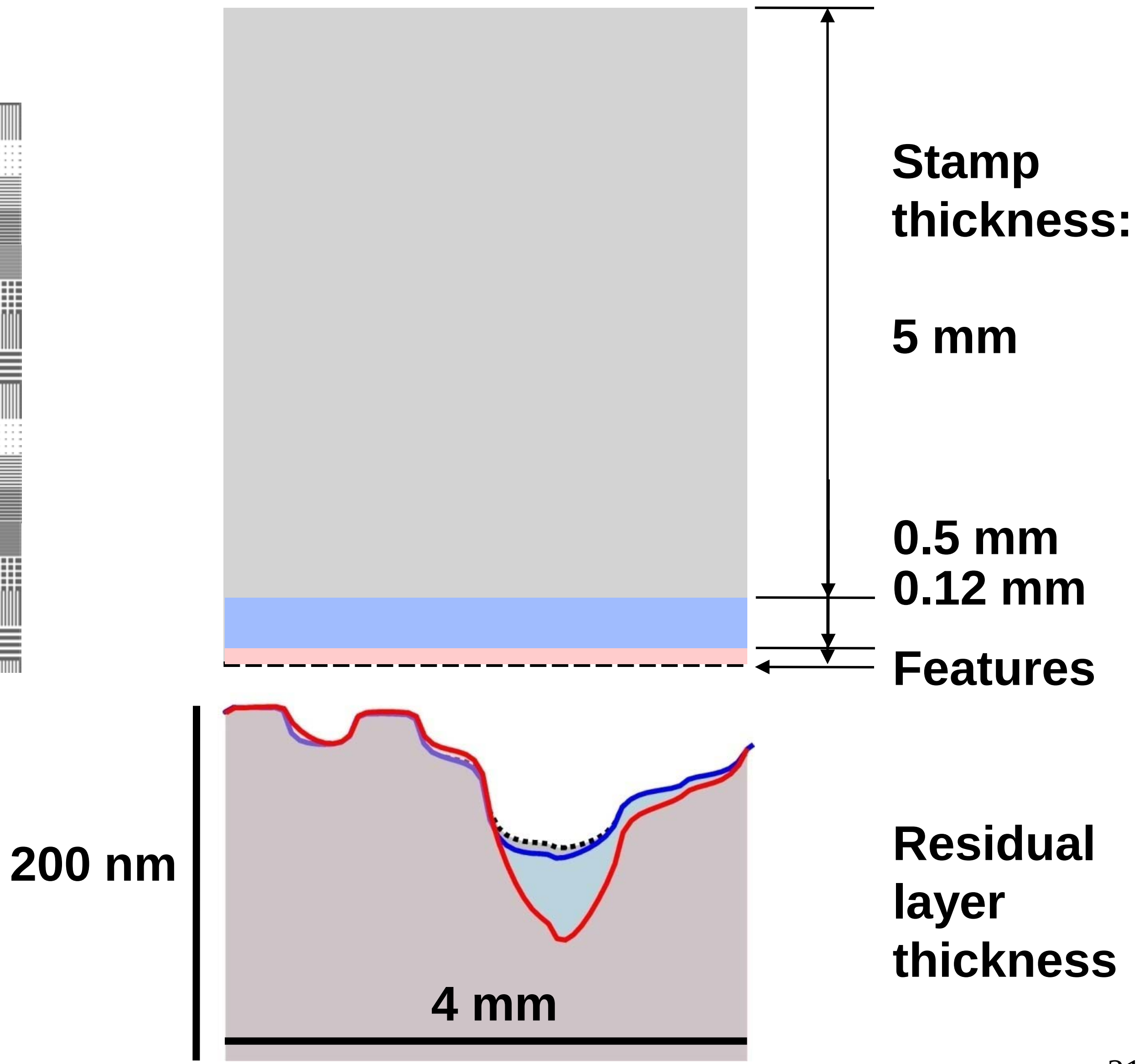
The physical insights of simulation can be encapsulated in design rules

- **Keep protrusion density *ρ* uniform**
  - Dummy fill insertion
  - Importance *grows* with lateral length-scale (unlike CMP)
  - Could vary cavity *heights* spatially*: expensive
- **Minimize *transient* stamp deflections: uniform $F_1\rho a^2$**
  - Care to avoid capillary bridging+ if some cavities unfilled
  - Impose upper limit on $F_1\rho a^2$ to limit filling time
  - Trenches quicker to fill than square holes => impose grid
- **Link to other process steps**
  - Exploit RLT variation to counteract etch nonuniformity
- **Pattern density rules, RLT variation target, stamp flexibility and substrate/stamp smoothness will be interrelated**

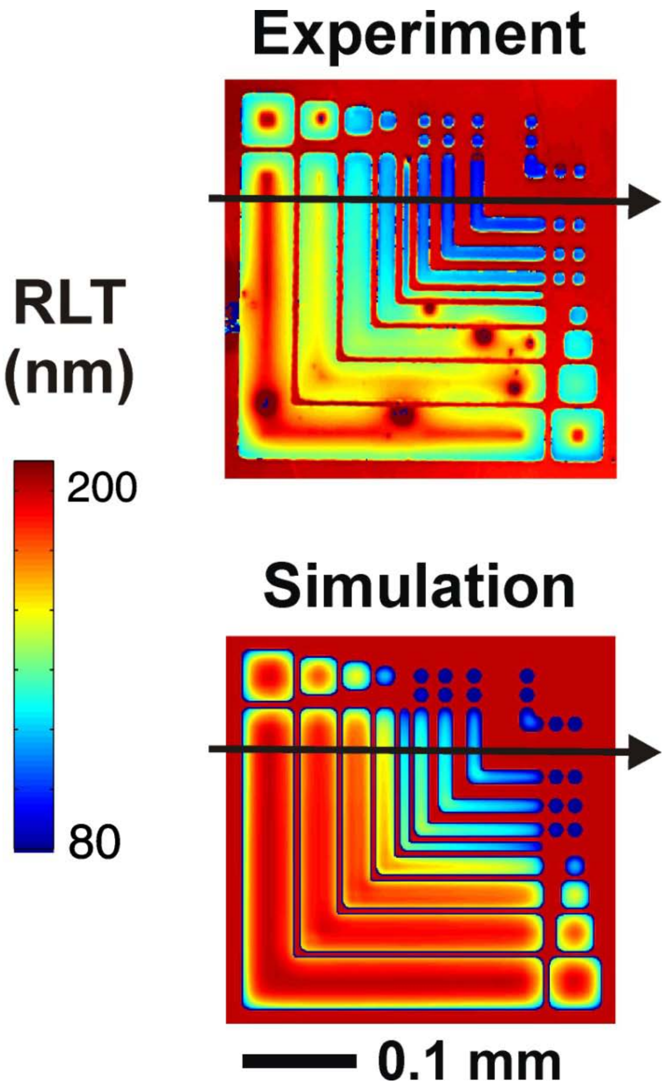
*** H. Hiroshima, in *Proc. Micro- and Nano-Engineering,* 2008.**
+ Landis *et al.*, *Microelectronic Eng.*, vol. 84, p. 940, 2007.

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 finite element modeling
- **Outlook**
  - We will need NIL-aware design checking
  - Can use as an engine for "Mechanical Proximity Correction"

Acknowledgements

- **Funding**
  - The Singapore-MIT Alliance
- **Colleagues**
  - Matt Dirckx, Eehern Wong, Melinda Hale, Aaron Mazzeo, Shawn Chester, Ciprian Iliescu, Bangtao Chen, Ming Ni, and James Freedman of the MIT Technology Licensing Office
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