Enabling layout and process optimization with fast, full-field simulation of droplet-dispensed UV-NIL

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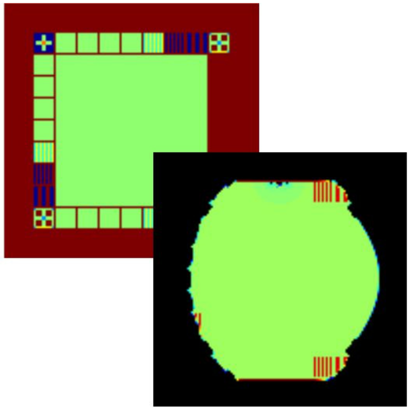
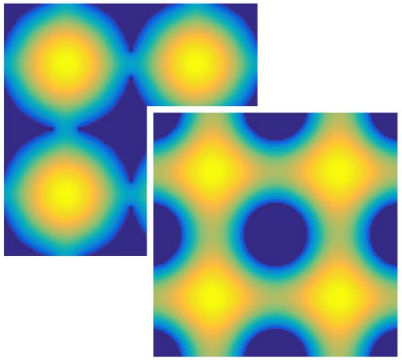
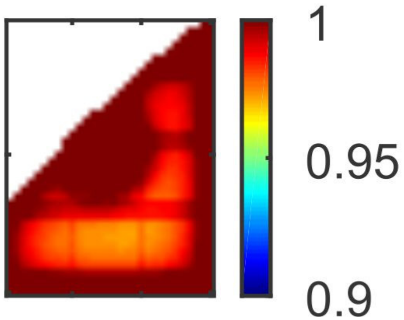
Outline: droplet-dispensed NIL simulation

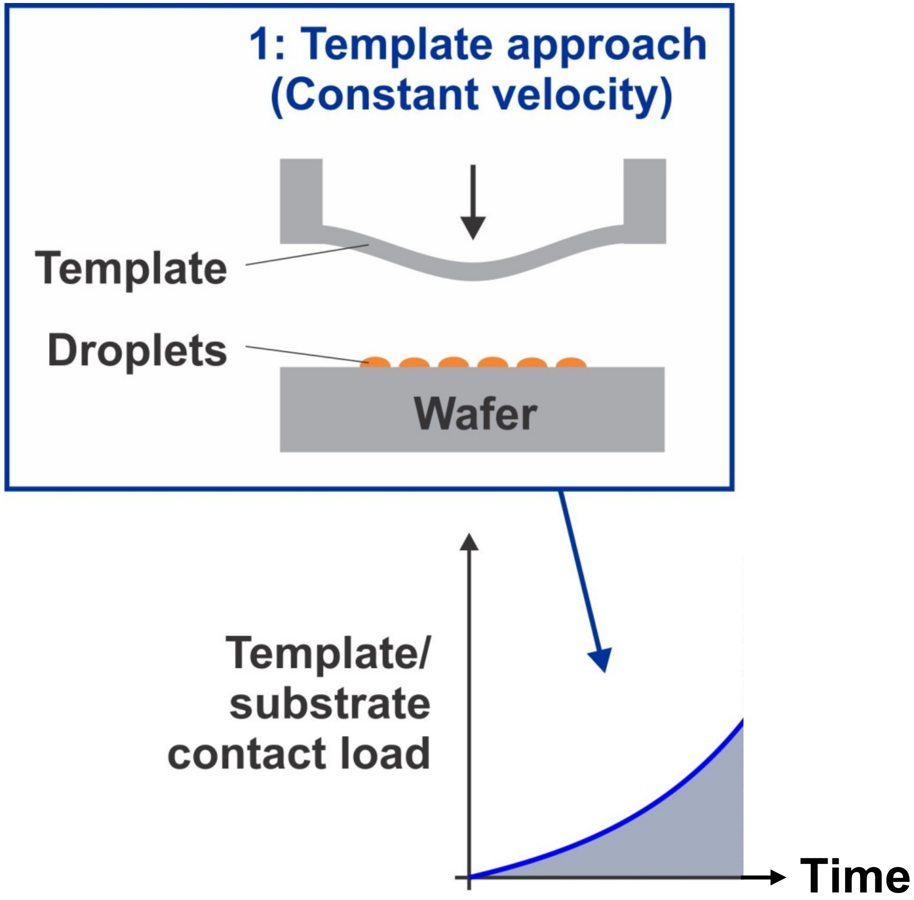
- Modeling objectives and key phenomena in droplet-dispensed NIL (JFIL)
- Capillary-driven droplet-spreading model
- Scalable model for merging of droplet arrays
- Integrated full-field simulation of JFIL
  - **Template edge effects**
  - **Wafer edge effects**
  - **Template curvature and avoiding gas entrapment**



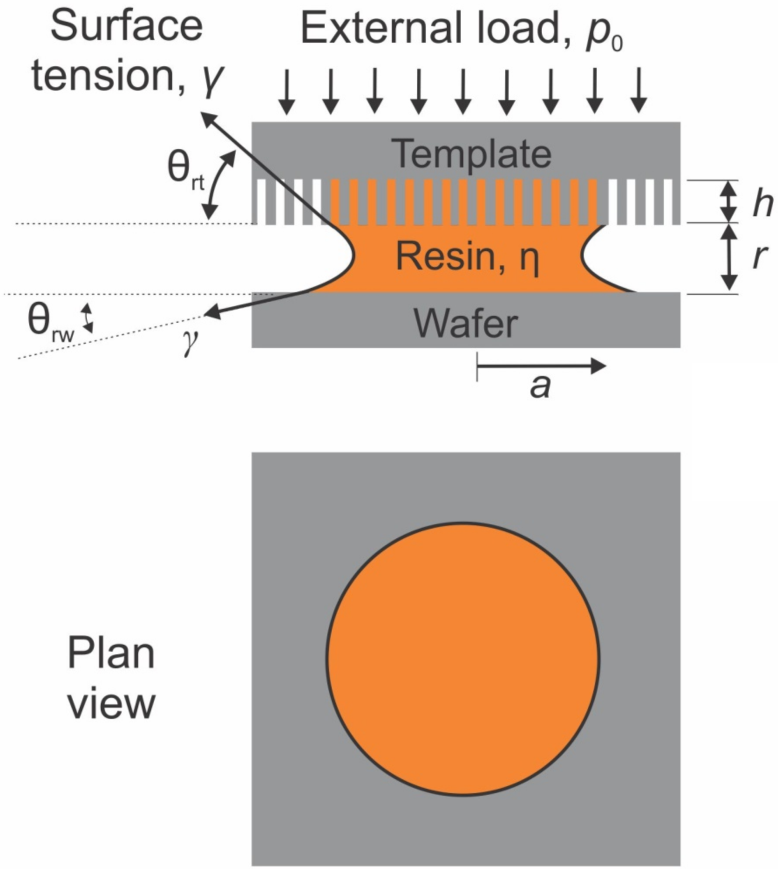




Droplet-dispensed simulation involves template approach, spreading and holding phases



Droplet spreading is driven by capillary and external loads, and can be highly directional



- Feature, droplet and chip length scales span 6 to 7 orders of magnitude – multiscale modeling is essential
- *Virtual work* concept used to capture work done by capillary forces

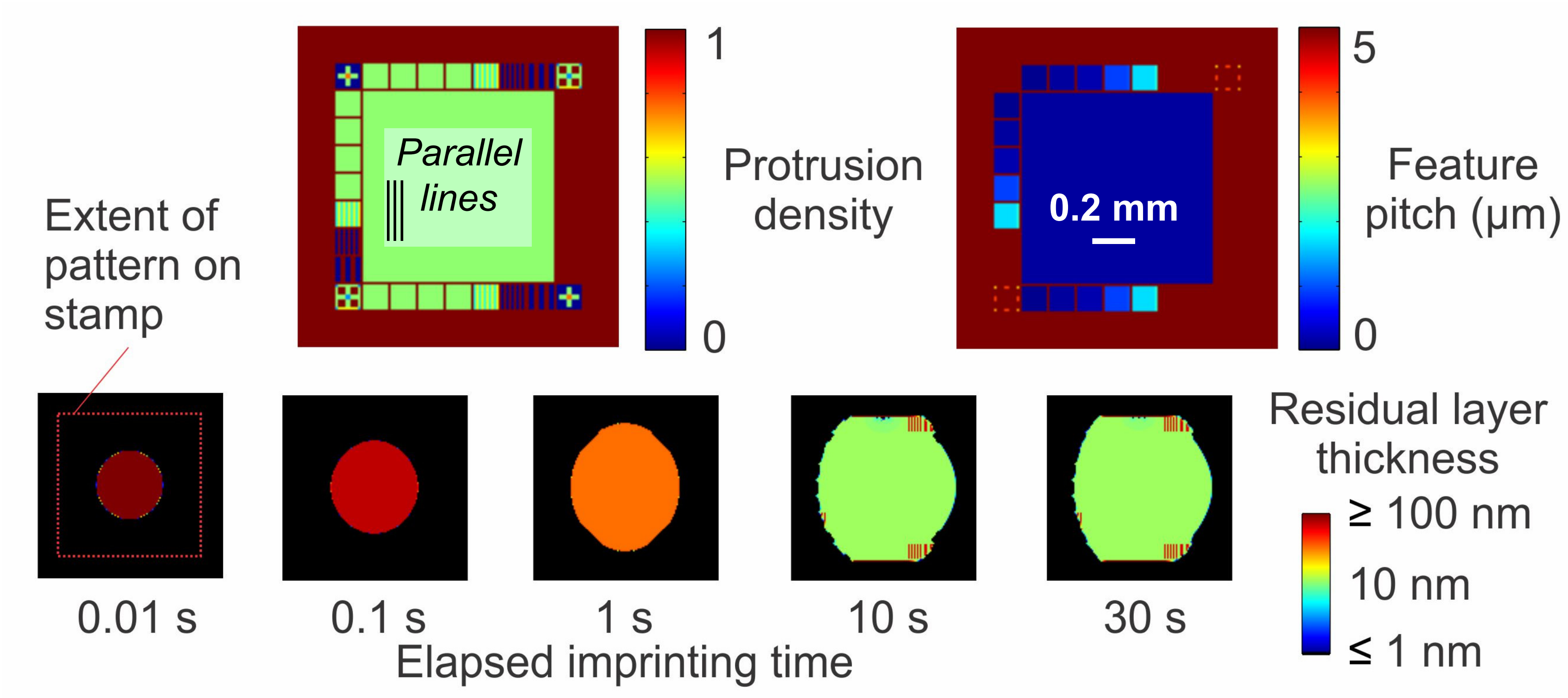
Droplet spreading is driven by capillary and external loads, and can be highly directional

- When droplet spreads beneath arrays of parallel lines, the resist impulse response is anisotropic, modeled with the following proportion of resist displacement directed parallel to the lines:

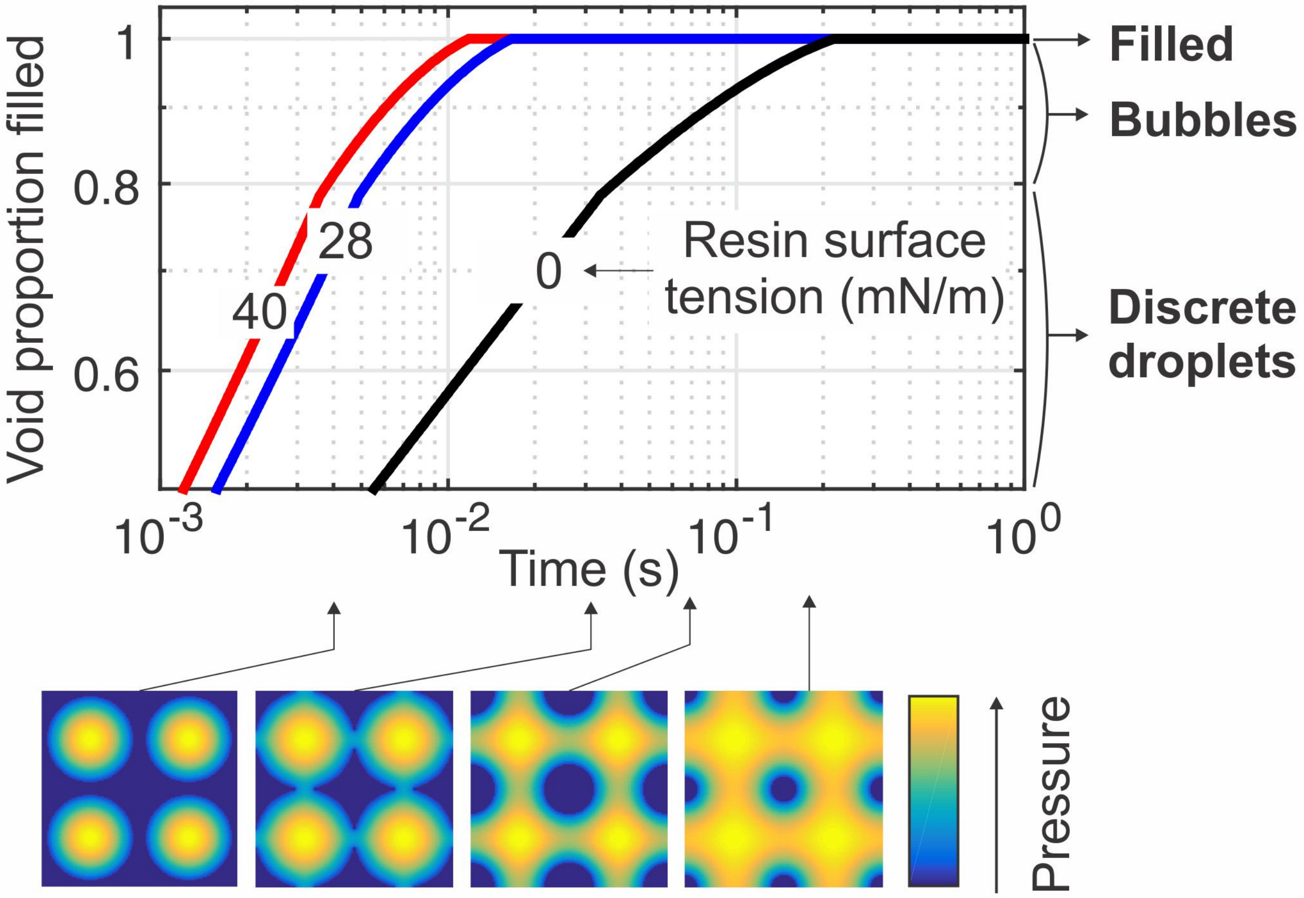
$$k_{parallel} = 0.75 + 0.25 \tanh\left(1.5 \log_{10} \frac{0.5h}{r}\right)$$

← Cavity height

← RLT



The spreading and merging behavior of regular arrays of droplets can be aggregated

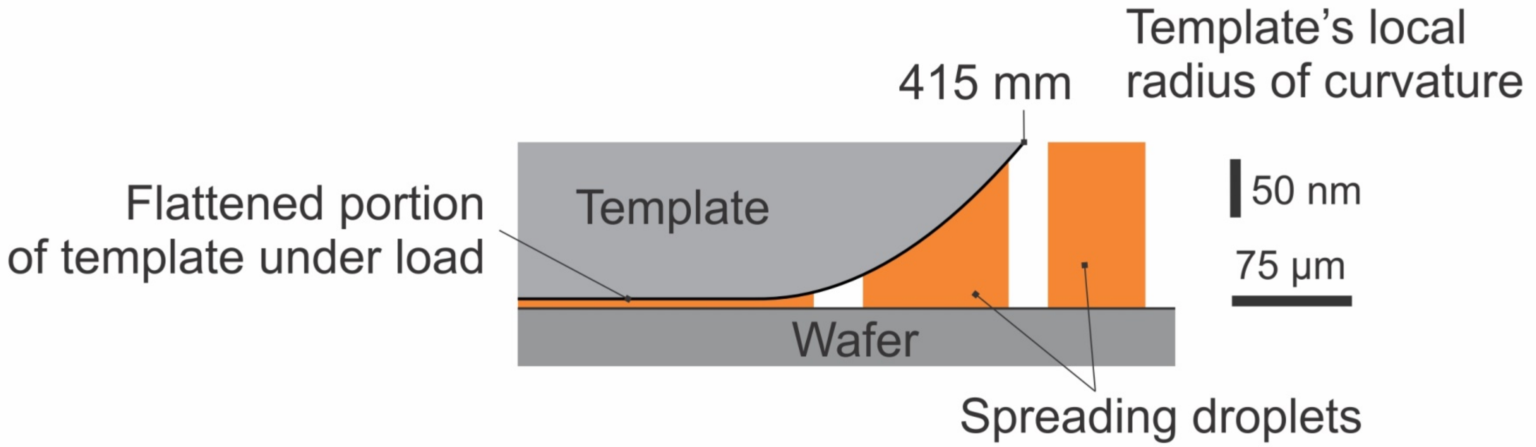


Pressure distributions in merging droplets

Example shown:

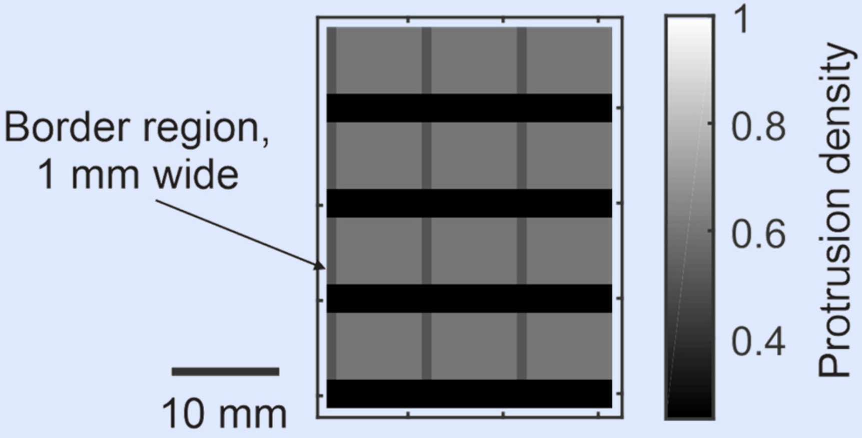
- Resin viscosity: 10 mPa.s
- External load: 40 kPa
- 1 pL droplets on 120 µm pitch
- Resin-template and resin-wafer contact angles: 15°
- Relationship captures both filling and RLT changes with time

Gas entrapment between merging droplets can be avoided by controlling template curvature



- **Fix curvature, bring stamp down under constant load, and droplets merge.**
- **If gas is entrapped, dissolution model would be needed; but aim is to avoid entrapment**

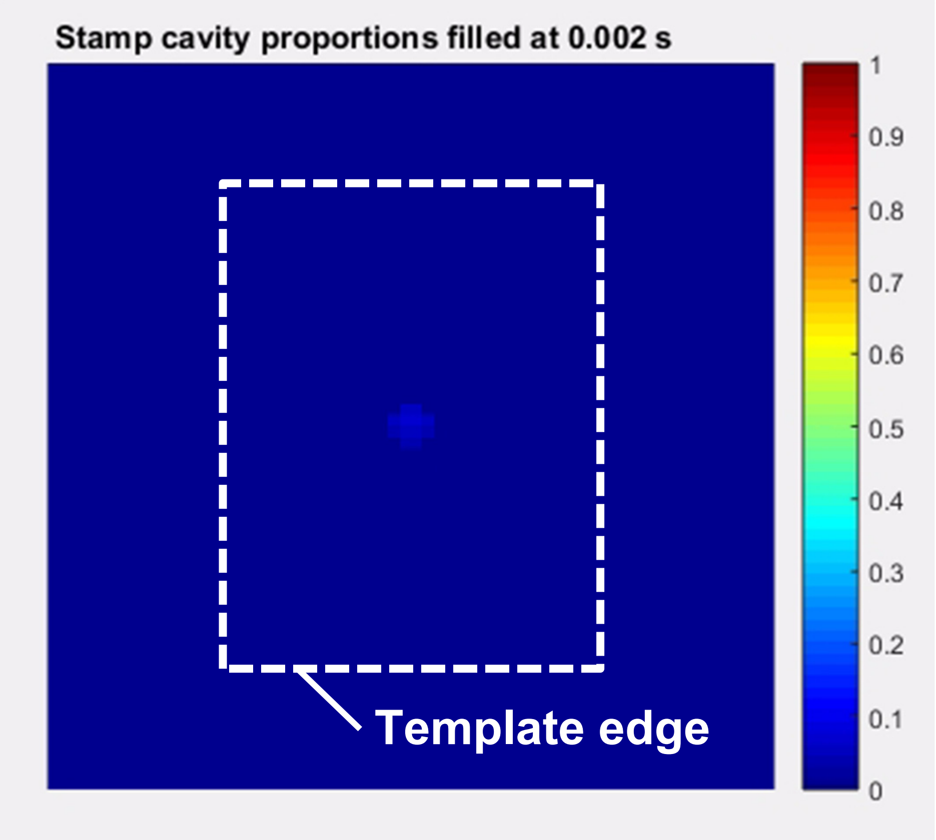
The time evolution of residual layer and cavity filling can be compared for multiple processes



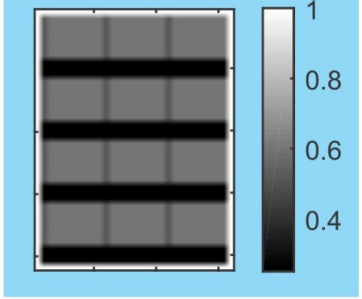
- **Example pattern, 30 mm x 40 mm template = single imprint field**
- **1 pL droplets; target RLT 25 nm**
- **Constant approach velocity of 50 µm/s until load of 50 N reached**
- **Load then maintained while template curvature relaxed over 1 second**

Animation of template cavity-filling over a six-second period

🟦 Empty → 🟥 Full



The time evolution of residual layer and cavity filling can be compared for multiple processes

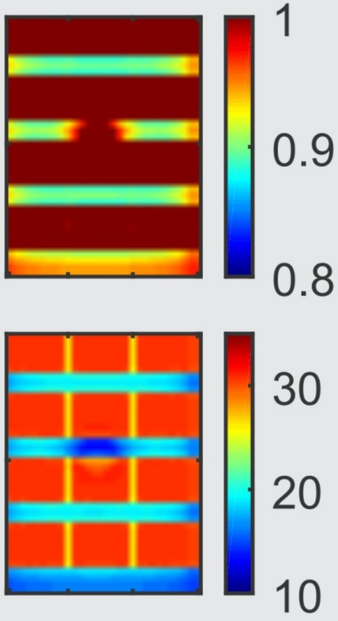

Protrusion density

Uniform droplet placement

Many unfilled features; highly nonuniform RLT

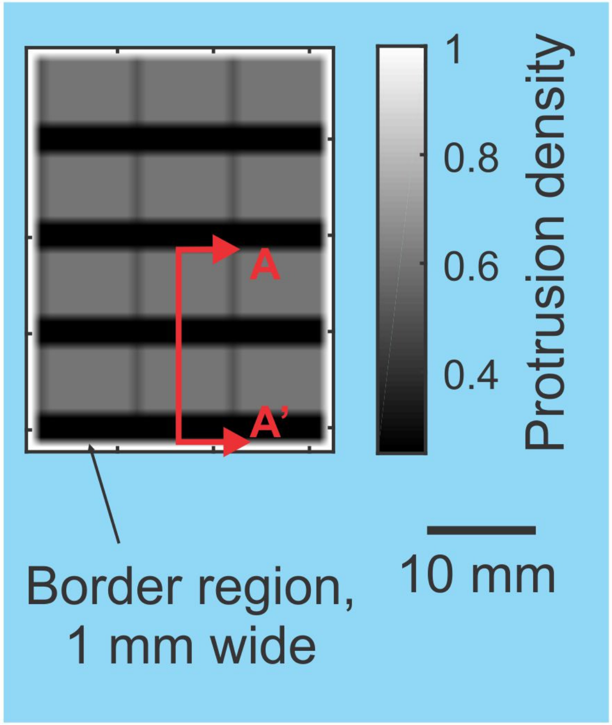
Cavity filling extent

RLT (nm)



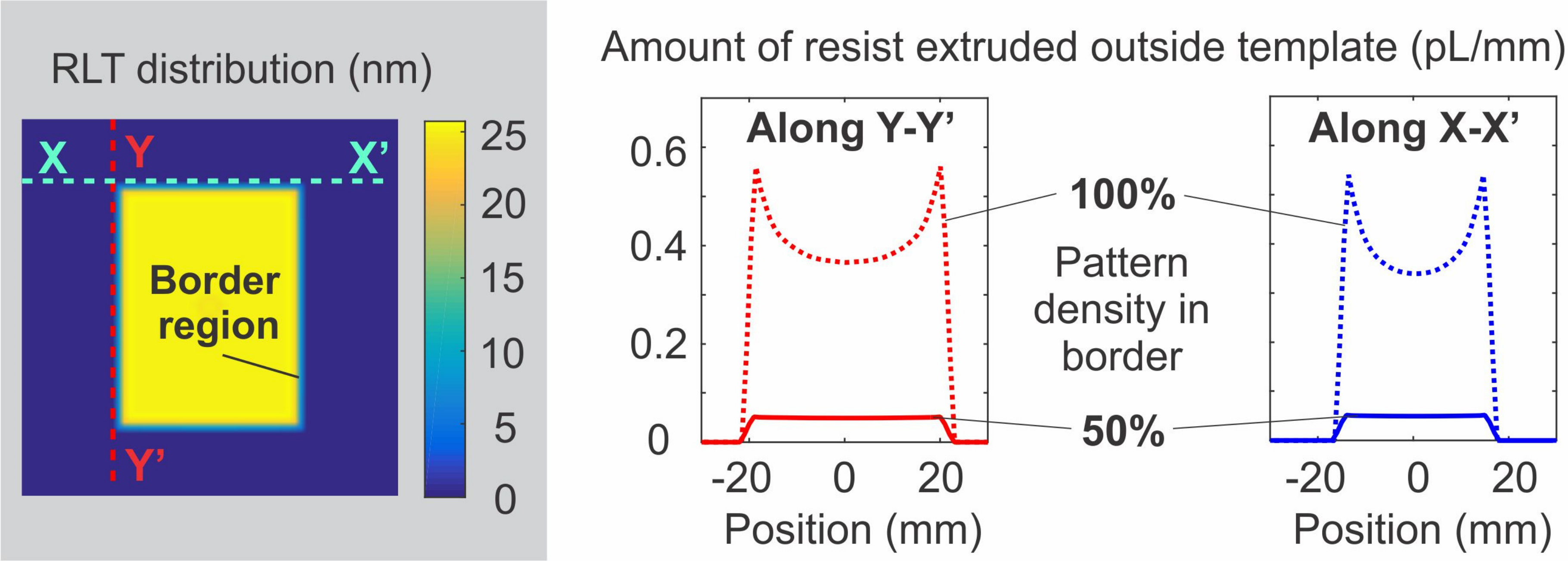
All cases after 1.3 s imprint time under equivalent loads

Template design near edge has a strong effect on edge RLT uniformity



- Pattern density and droplet distribution near template edge may be tuned to compensate for pressure nonuniformities there and achieve uniform RLT

Extrusion of resist at template edge can be simulated and optimized



- Material squeezed out from edge of template costs silicon real estate: simulations can predict this
- A slight surplus of template cavity volume in the border may be used to suppress resist extrusion

Outlook

- JFIL simulation algorithm incorporating effects of pattern-dependent capillary pressures, external loads, and template bowing. Easily scales to >10,000 droplets.
- Predicts RLT uniformity and template filling evolution
- Provides insights into template edge extrusion and likelihood of gas entrapment
- Simulation speed and resolution can be tuned
    - For a 30x40 mm field simulated on an Intel i7, 8 GB RAM: ~5 seconds at 1 mm resolution; ~5 mins at 0.1 mm resolution
- Detailed (pre-)production data needed for model calibration
    - Locations and frequencies of defects within imprint fields, and spatial maps of RLT
    - Data needed for multiple template curvature relaxation cases and spread/hold times

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