Nanometer Scale Patterning and Processing

Spring 2016

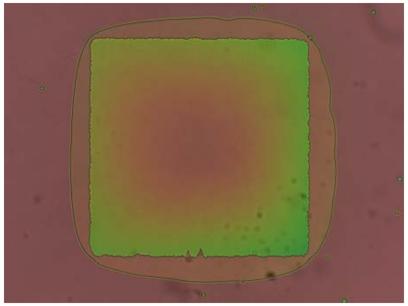
Lecture 34

Nanoimprint Lithography (NIL) – Pattern Dependence in Nanoimprint

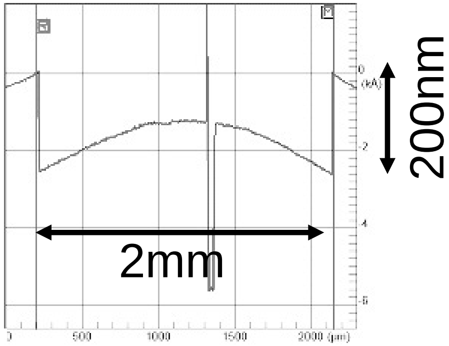
Another way to reduce residue layer effect: use tri-layer (or bi-layer) resist

Square (mm) imprinted into PMMA

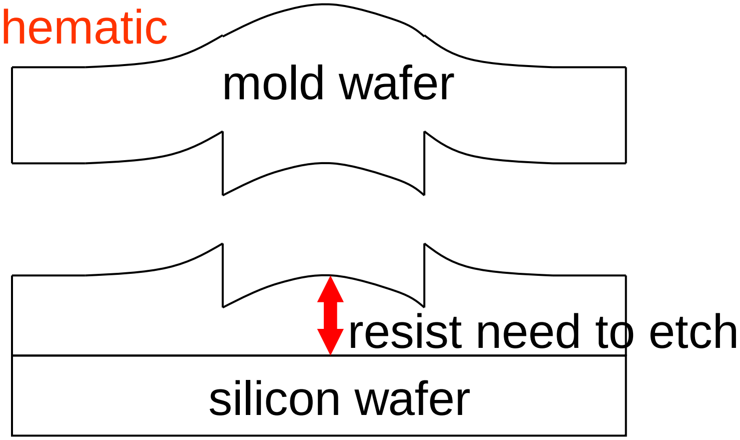
Optical image



Profile

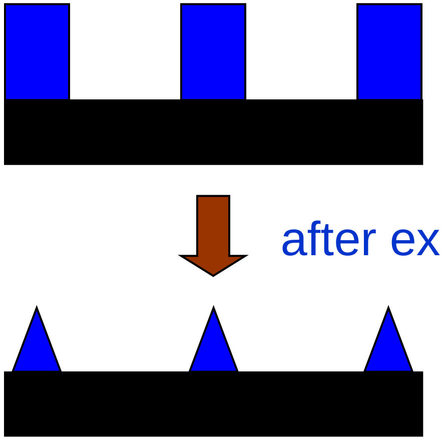


Schematic

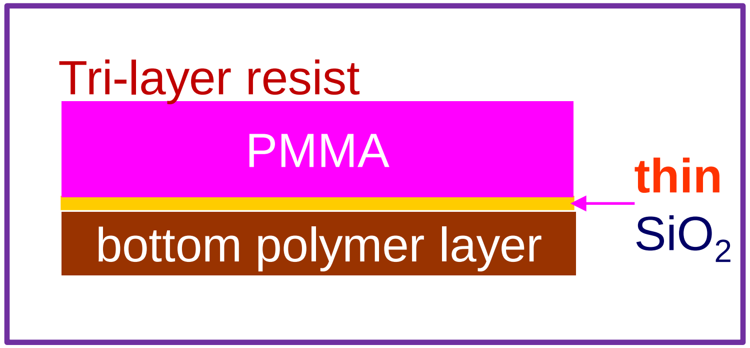


Need excessive etch to remove the thick resist at the square center

But for nanoscale features…



Such a profile makes liftoff difficult.
Solution: use tri-layer resist system

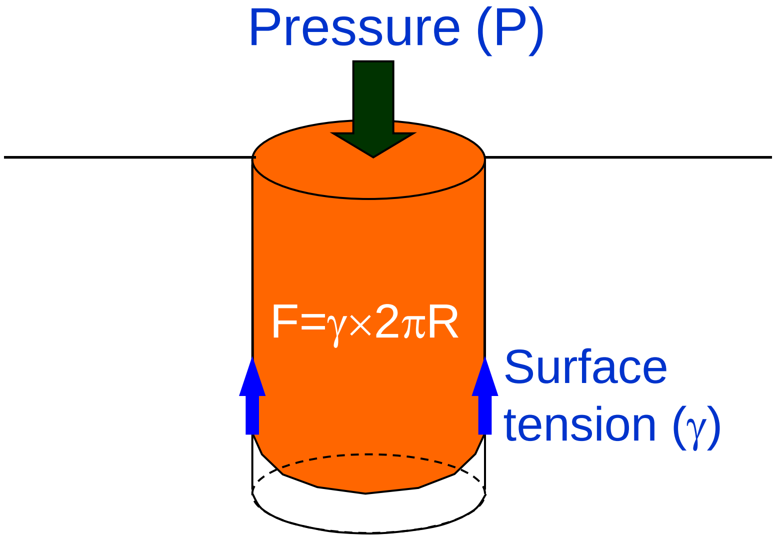


- Section 3

PATTERN DEPENDENCE IN NANOIMPRINT

NIL for small features/high resolution (<10nm)

Press liquid into a nano-hole

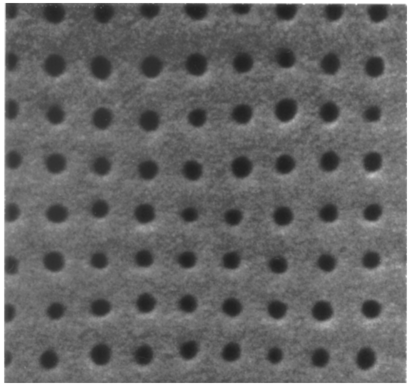

Pressure (P)

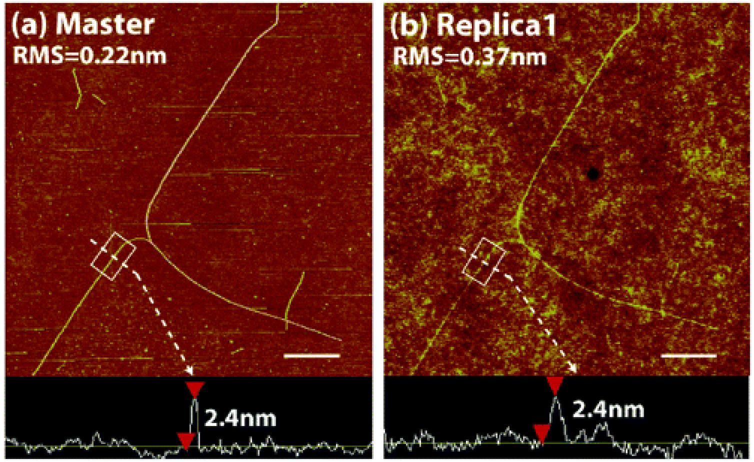
F=γ×2πR

Surface tension (γ)

$$P = \frac{\gamma \times 2\pi R}{\pi R^2} = \frac{2\gamma}{R} \propto \frac{1}{R}$$

- Pressure ∝ 1/diameter.
- But for protruded mold features (pillars…), local pressure at the pillar is much higher than average - easy to imprint.


Thermal NIL into PMMA (10nm pillar array mold)



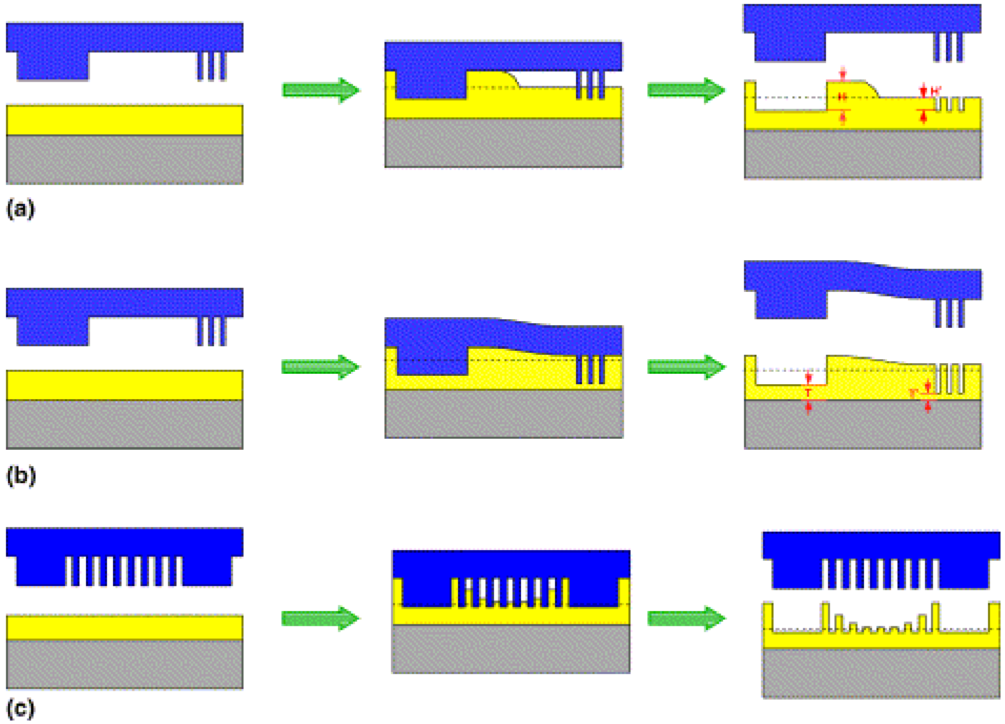
UV-curable NIL, **2nm** carbon nanotube mold

Hua … Rogers, “Polymer imprint lithography with molecular-scale resolution”, Nano Lett. 2004

NIL for large features (>100 μm) - simultaneous pattern duplication of large and small features

- Application: large features are needed to connect small ones to the outside world (electrodes…).
- Challenge: more polymer must be displaced over longer distances.
- A popular approach: two-step process - small features by NIL, large ones by photolithography with alignment.

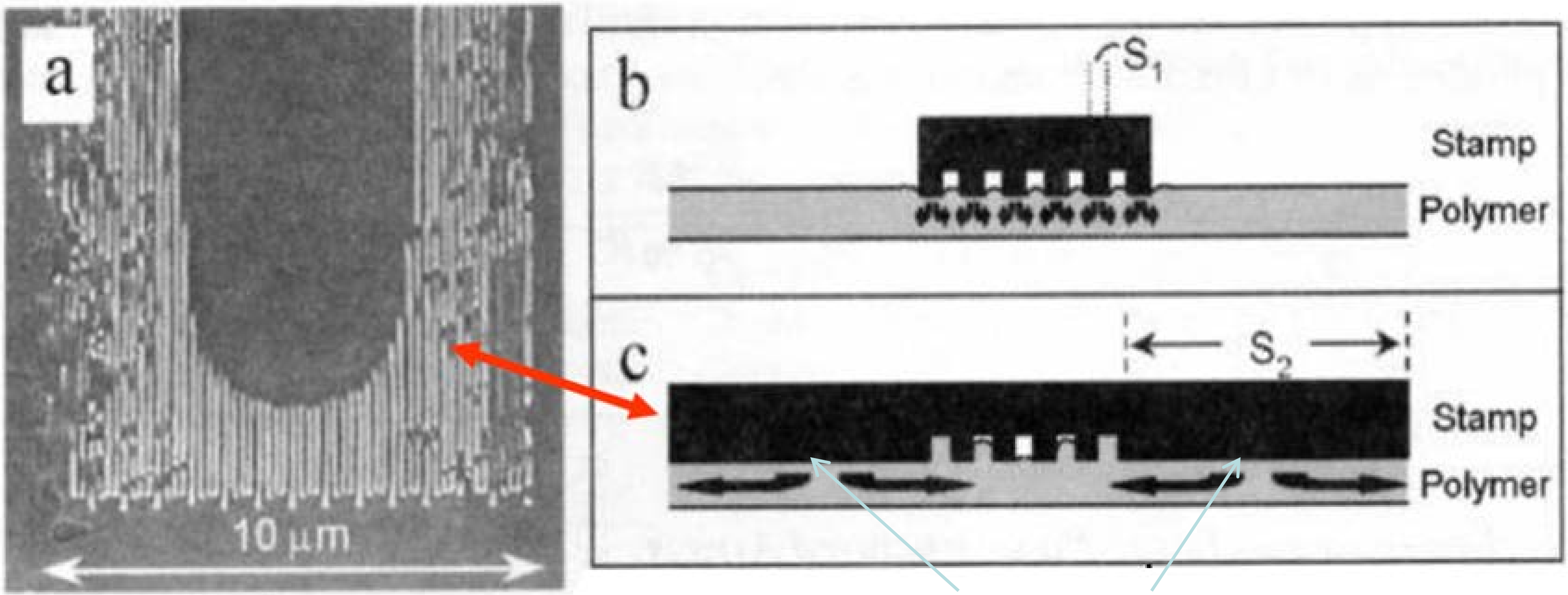
Problems when both small and large features are present



Schematics of pattern failure mechanisms in NIL as a result of: (a) non-uniform pattern height; (b) non-uniform residual layer thickness; (c) incomplete nano-pattern replication.

Cheng, "One-step lithography for various size patterns with a hybrid mask-mold", Microelectronic Engineering 71, 288–293 (2004).

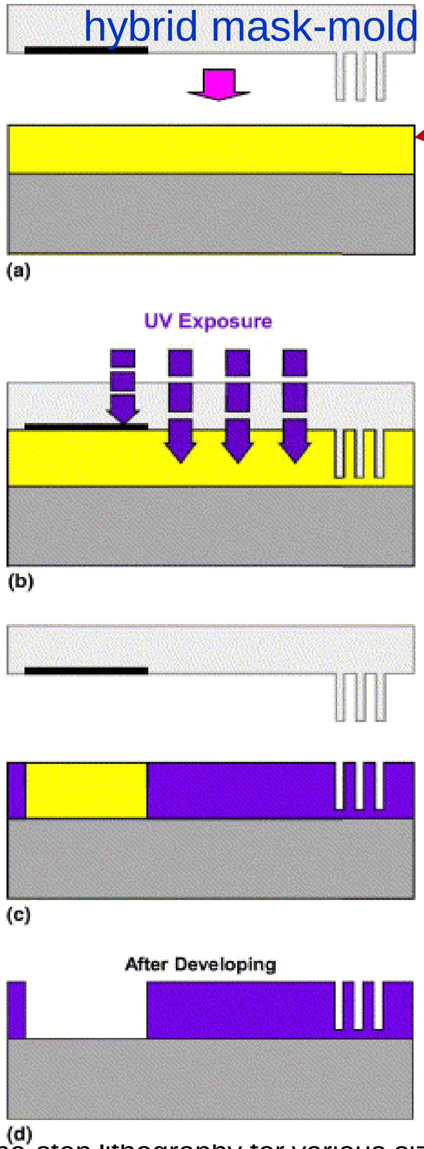
NIL pattern uniformity



Etch some dummy holes/trenches here

- The fill factor should be kept constant: better flow and shorter imprint time.
- Different fill factor across mold leads to different sinking rates.
- Mold bending leads to non-uniform residual layer on substrate.
- One solution: fabricate dummy cavities/protrusions to create constant fill factor.

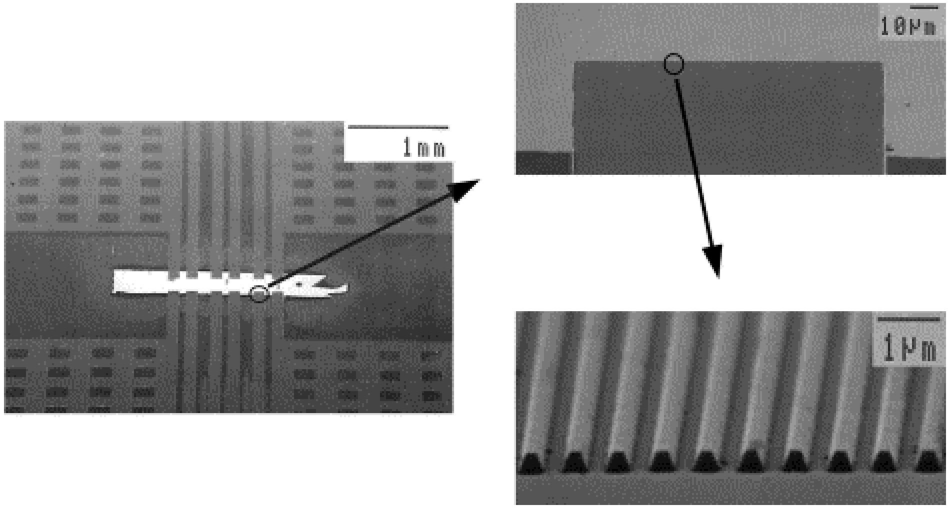
Combined UV (for macro) and nanoimprint lithography (for nano)



SU-8 is used both as a photo-resist and thermal NIL resist.

(SU-8 is a photo-resist, but not a UV-NIL resist (hard to imprint at RT). Instead, it can be used as a thermal NIL resist, $T_g \sim 50^{o}C$)

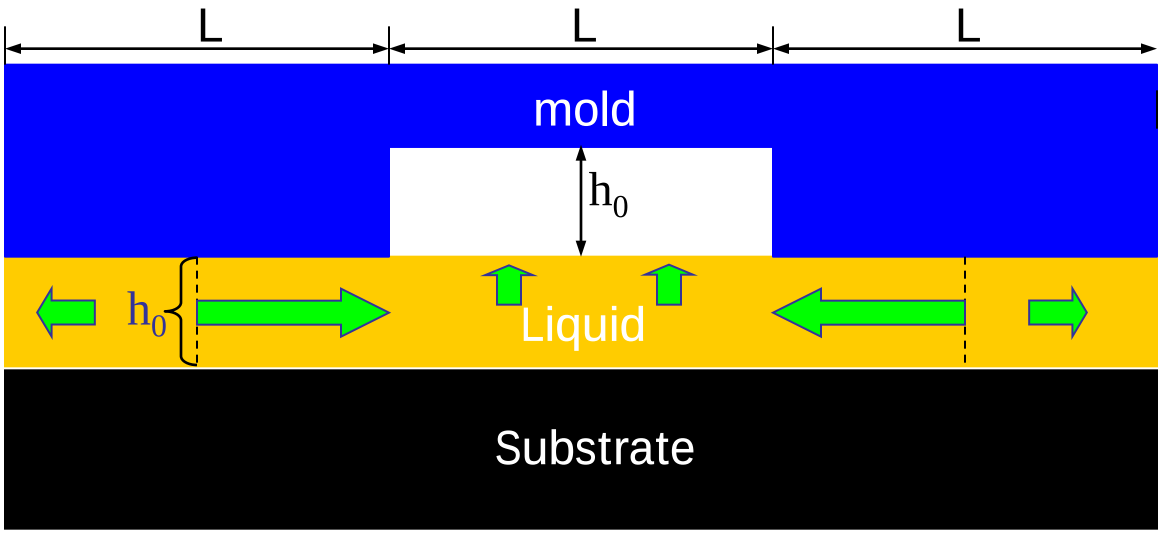
Schematics of the technique by using a hybrid mask-mold for one-step lithography of both large- and nano-patterns



SEM micrograph of resist patterns obtained by the technique with hybrid mask-mold.

Cheng, “One-step lithography for various size patterns with a hybrid mask-mold”, Microelectronic Engineering 71, 288–293 (2004).

Modeling of liquid flow for large features (>>pattern depth)



Assumptions:

- Periodic mold structure (period 2L)
- Ignore inertial, gravitational forces and surface tension
- Resist film thickness = mold trench depth = h_0

$$L = \frac{2h_0}{3}\sqrt{\frac{p\tau}{\mu}} \propto \left(\frac{p\tau}{\mu}\right)^{1/2}$$

L: achievable feature size

p: pressure

τ: imprinting time

μ: viscosity

h_0: film thickness

Strategy to imprint large features (mm)

$$L \propto \left(\frac{p\tau}{\mu} \right)^{1/2} \propto \frac{1}{\sqrt{\mu}}$$

L: achievable feature size
p: pressure
τ: melting time
μ: viscosity

For thermoplastic polymer PMMA at T>T_g

$$\boxed{\log \mu = n \log M_w - \frac{12.21(T - T_g)}{70.1 + (T - T_g)} + const}$$

M_w: molecular weight
n=1 for M_w<M_C, un-entangled molecules
n=3.4 for M_w>M_C, entangled molecules

Viscosity for PMMA (M_c=30kg/mol)
a) 12 kg/mol, 200°C; b) 12 kg/mol,150°C; c) 120 kg/mol, 200°C

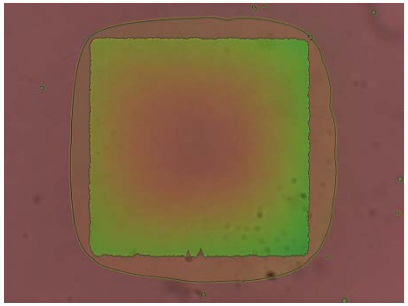
$\mu_a:\mu_b:\mu_c$=1:126:278

Use low molecular weight PMMA and imprint at high temperature

Strategy to imprint large features (mm)

Square (mm) imprinted into PMMA

Optical image



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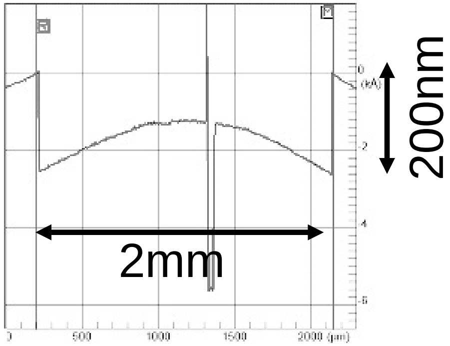
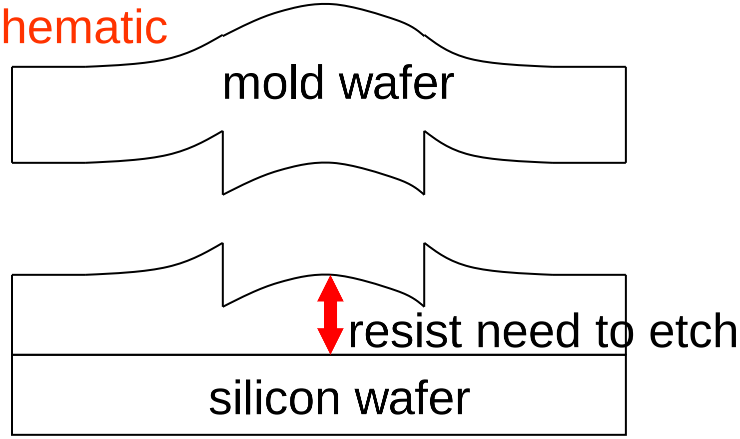
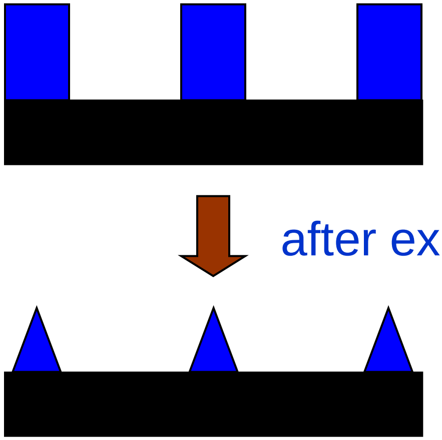


Schematic

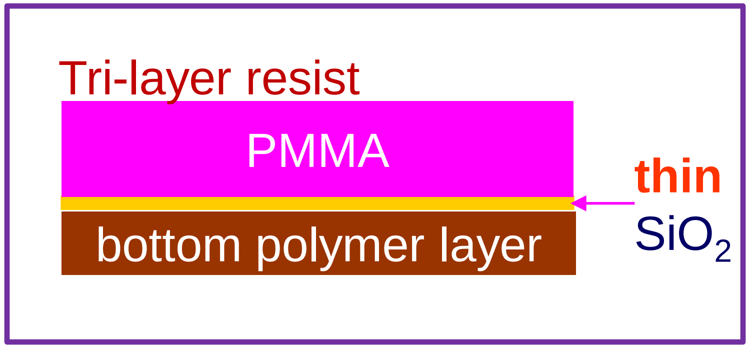


Need excessive etch to remove the thick resist at the square center

But for nanoscale features…



Such a profile makes liftoff difficult.
Solution: use tri-layer resist system



Tri-layer resist

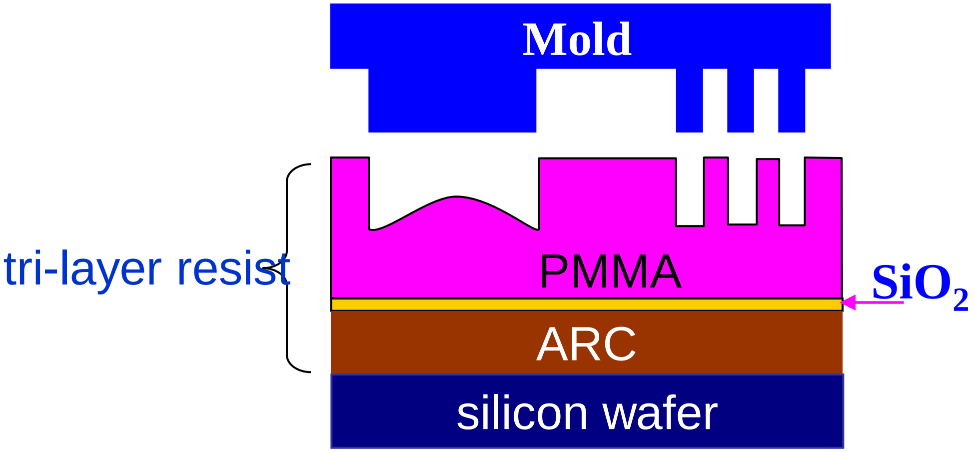
PMMA

thin SiO_2

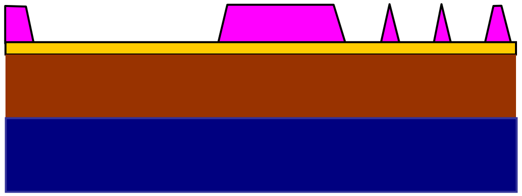
bottom polymer layer

Fabrication process flow

ARC: Anti-reflection coating, cross-linked polymer.



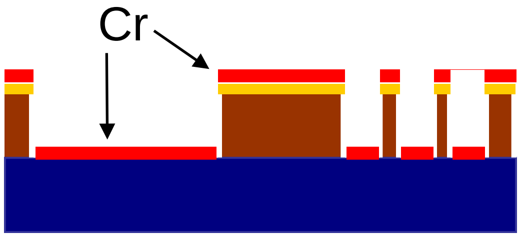
1. Imprint



2. RIE PMMA (excessive etch)

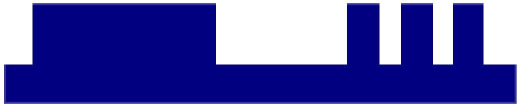
3. RIE SiO_2 (CHF_3 gas)

4. RIE ARC (O_2 gas, etch little SiO_2)



5. Evaporate Cr

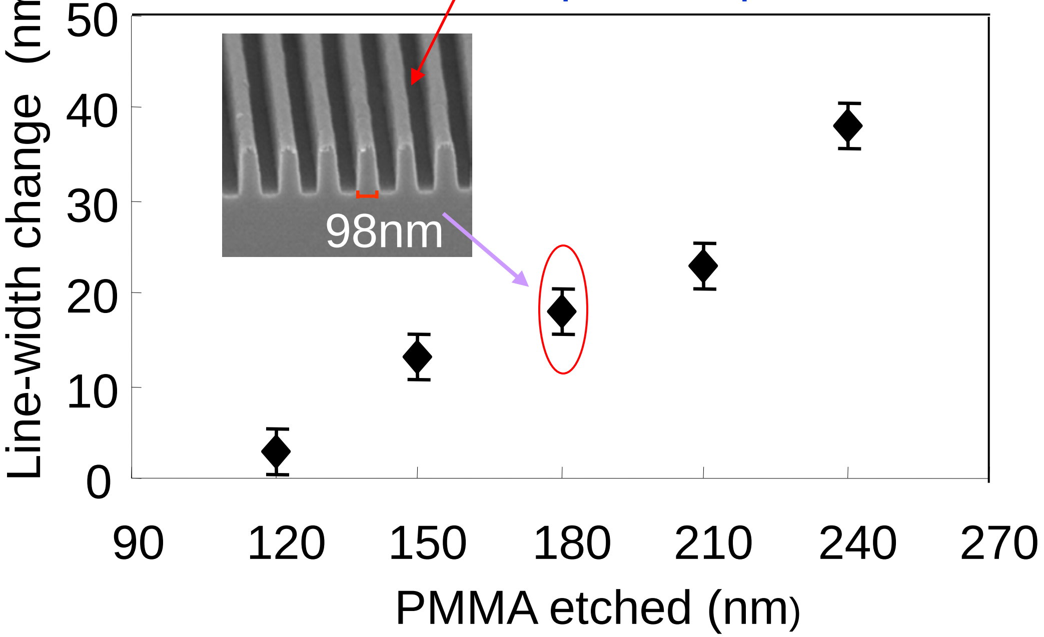
6. Liftoff Cr (dissolve ARC)



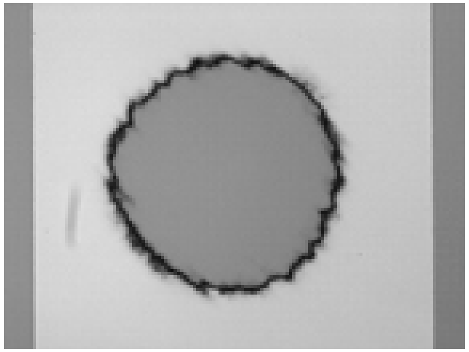
7. RIE Si (etch little Cr)

Result

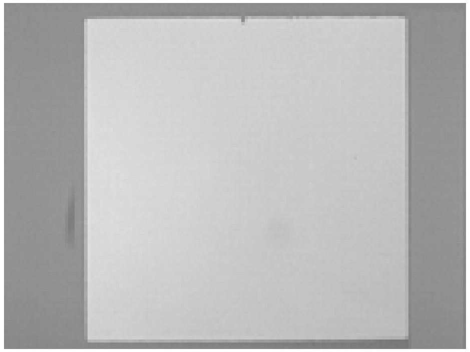
Line-width in the mold is 80nm
Line-width in the duplicated pattern is 98nm



1.6mm square



1.3mm square



(RIE PMMA 180nm)

For small features, line-width increased by ~18nm (acceptable).
For large features, 1.3mm squares were faithfully duplicated.

Cui and Veres, “Pattern replication of 100 nm to millimeter-scale features by thermal nanoimprint lithography”, MEE, 2006