High-throughput screening of adhesion and release in nanoimprint lithography

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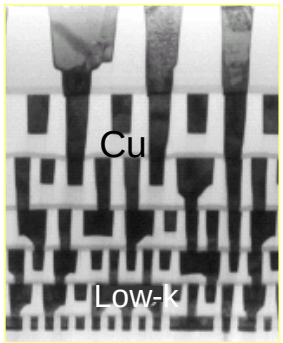
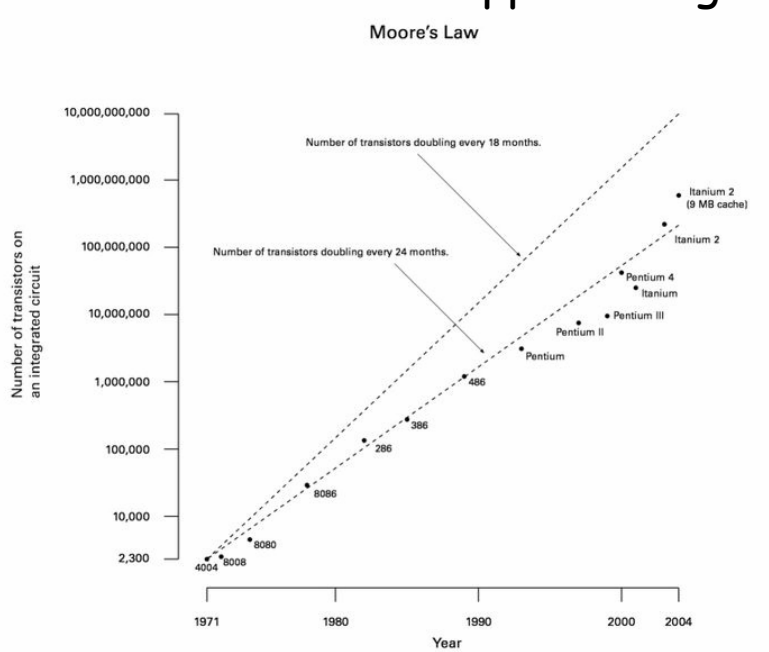
Introduction

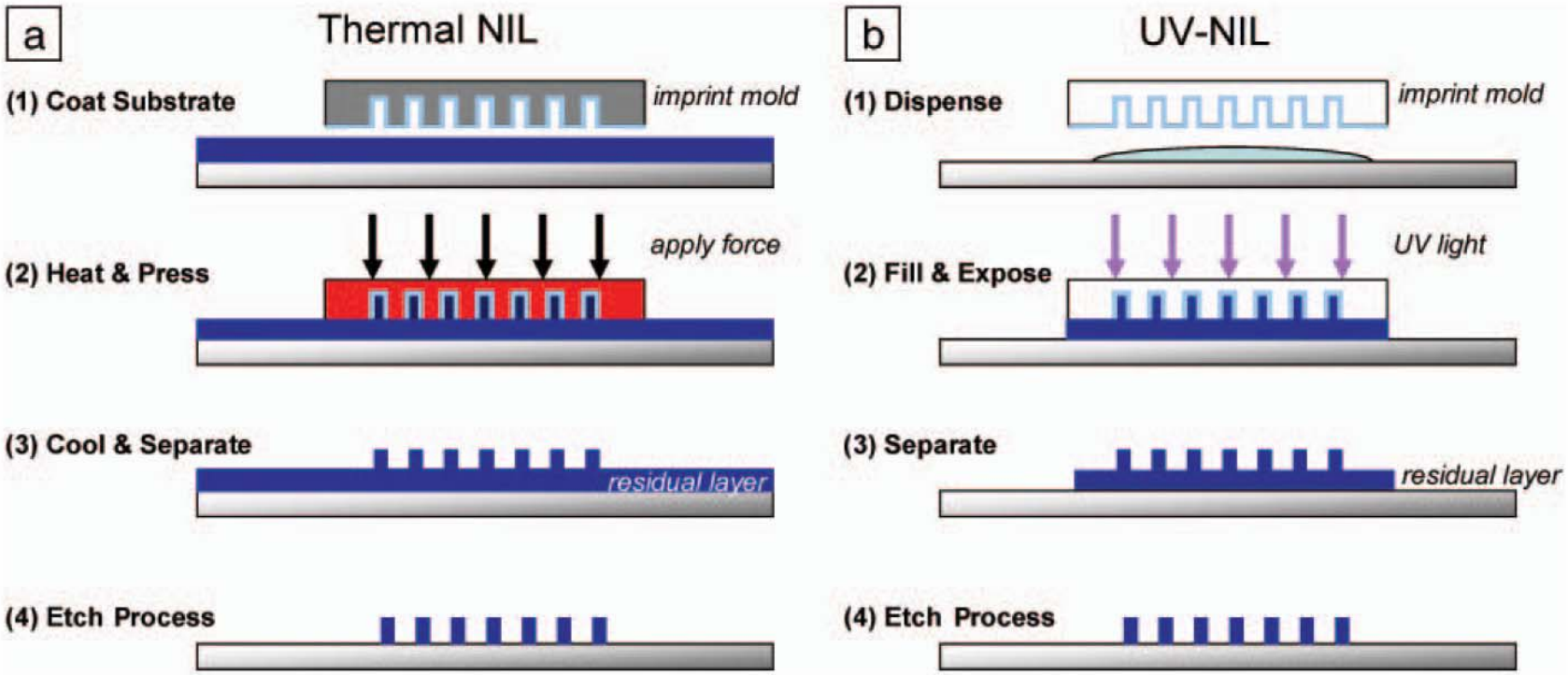
- Advanced microprocessors are comprised of multilevel interconnects of Cu and low-k material with the minimum feature size approaching 50 nm.





- As features continue to get smaller, current technologies will not be able to keep up with Moore's Law…
- Nanoimprint lithography (NIL) is a low-cost, high-resolution next-generation lithographic technique.

Nanoimprint Lithography



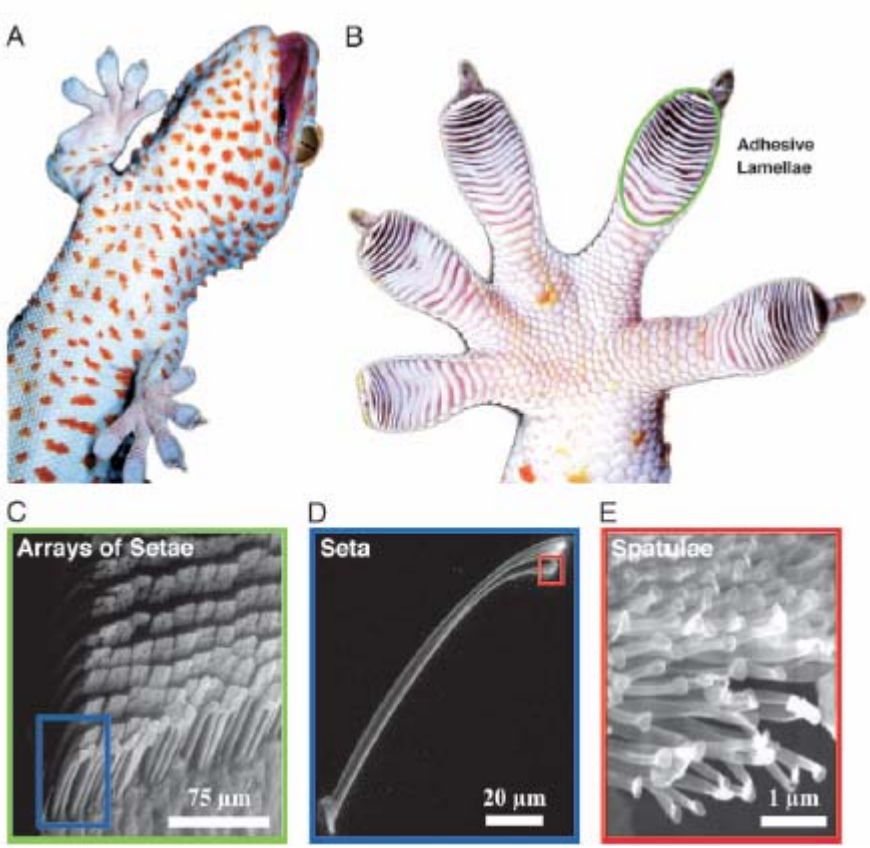
S.Y. Chou *et al.*, *Appl. Phys. Lett.* **67**, 3114 (1995)

C.G. Willson *et al.*, *Proc. SPIE* **3676**, 379 (1999).

Image from: M.D. Steward and C.G. Willson, *MRS Bulletin* **30**, 947 (2005).

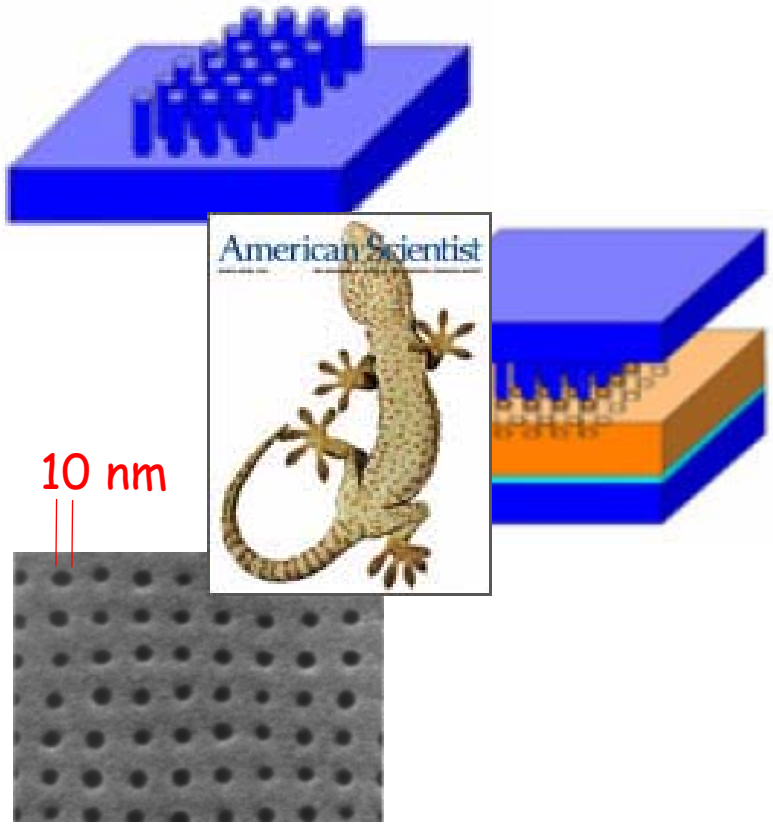
Adhesion to Patterned Surfaces

Lessons from mother nature



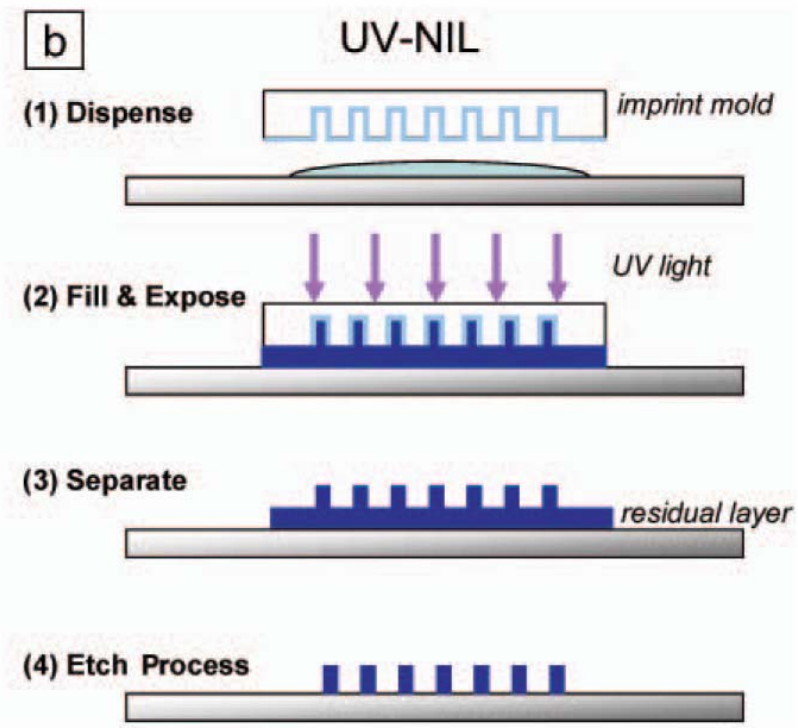
- Nanoscale spatulae provide enormous surface area
- van der Waals interaction huge

Implications for Nanoimprint



- Surface forces / van der Waals interactions will be important!

Nanoimprint Lithography



ADVANTAGES

- Cheap and Easy Process
- No Feature Size Limitations
- High Throughput

DISADVANTAGES

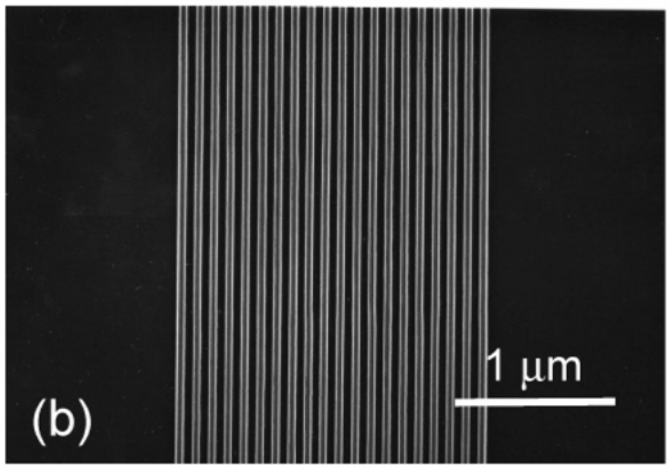
- Mold Adhesion to the resist
- Unknown or Varying Residual Layer Thicknesses

APPLICATIONS

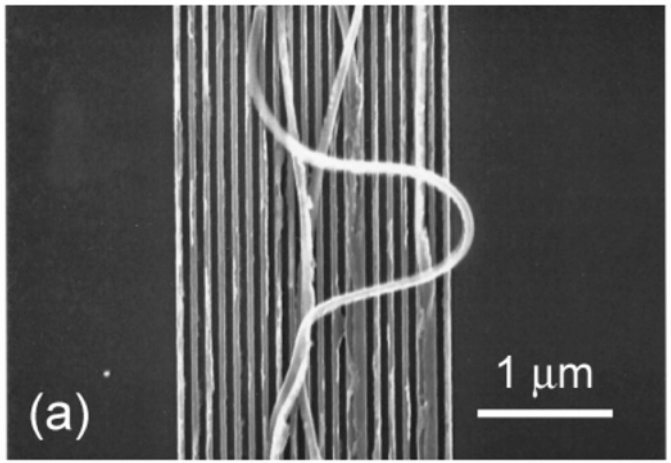
- Semiconductor chips
- Nanofluidic devices

Adhesion Issues

mold

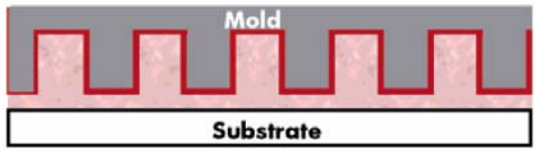


mold after imprinting



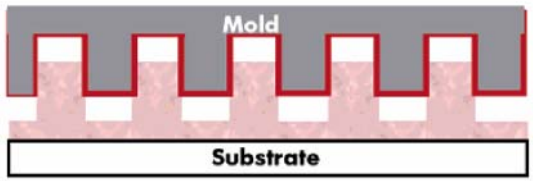
G.-Y. Jung et al. *Langmuir* **21**, 6127 (2005).

Adhesion in UV-NIL



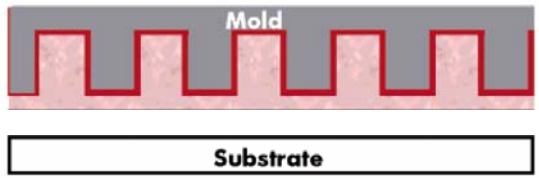
$$G_i = A_{r-s}\gamma_{r-s} + A_{r-m}\gamma_{r-m}$$

Case I



$$G_f = A_{r-s}\gamma_{r-s} + A_{r-m}(\gamma_r + \gamma_m)$$

Case II

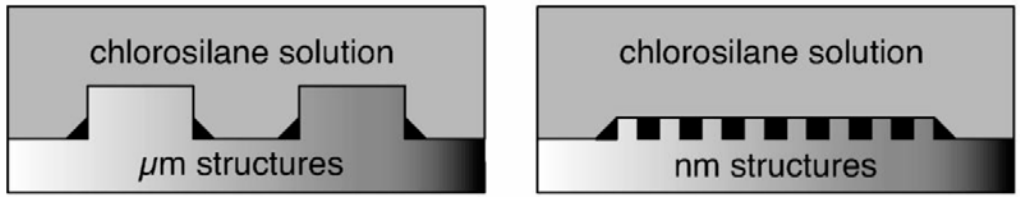


$$G_f = A_{r-m}\gamma_{r-m} + A_{r-s}(\gamma_r + \gamma_s)$$

$$\Delta G_{detach} < \Delta G_{adhere}$$

$$A_{r-m}(\gamma_r + \gamma_m - \gamma_{r-m}) < A_{r-s}(\gamma_r + \gamma_s - \gamma_{r-s})$$

G.-Y. Jung et al. *Langmuir* **21**, 6127 (2005).



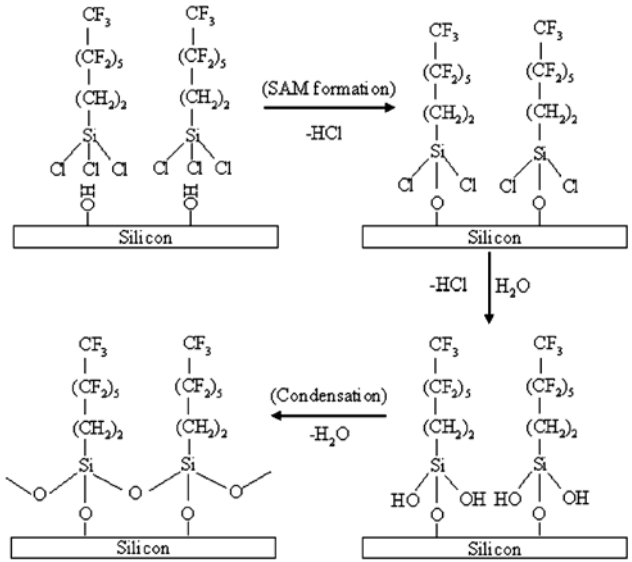


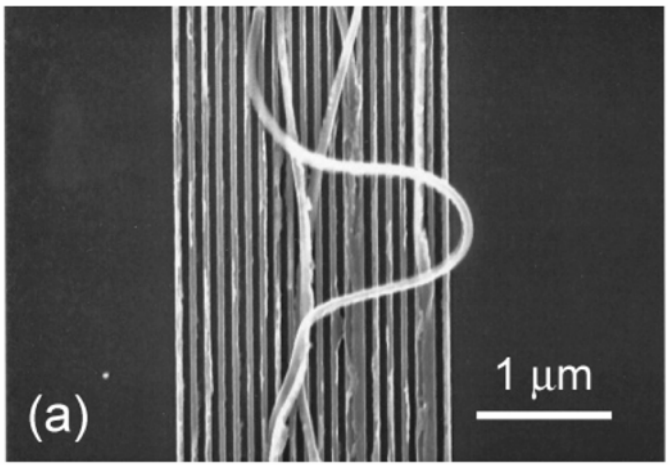
Table 1. Water Contact Angle and Ellipsometric Thickness of the Vapor-Phase SAMs Formed Under Different Conditions

sample preparation	sessile contact angle (deg) (water)	ellipsometric thickness (nm)
1 cycle w/o water vapor	100	0.66
1 cycle	108	0.64
2 cycles	112	0.94
3 cycles	113	0.95

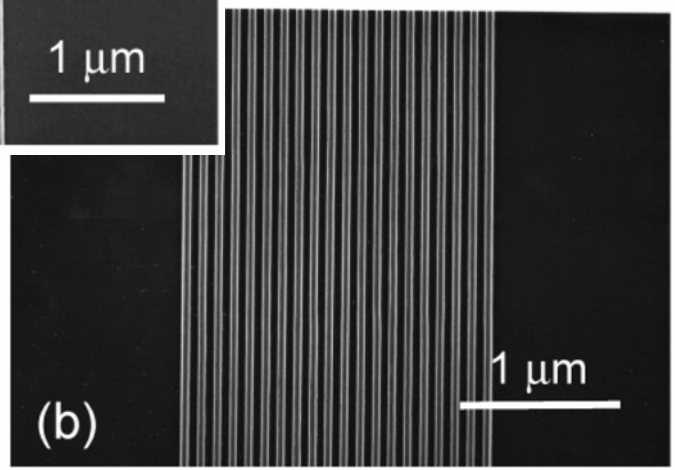
M . Beck *et al.*, *Microelectronic Engineering* **61– 62**, 441 (2002).
G.-Y. Jung *et al.*, *Langmuir* **21**, 1158 (2005).

Adhesion

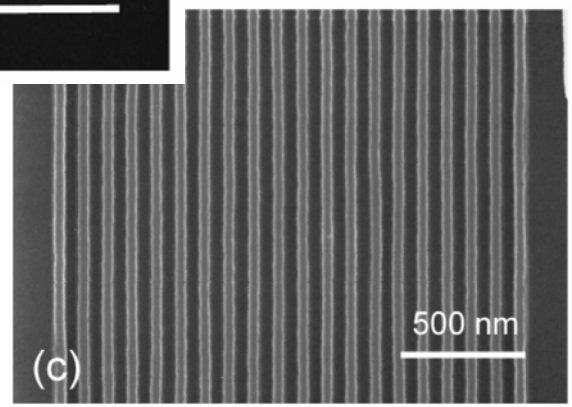
Mold w/ high adhesion (untreated or solution phase)



Mold w/ low adhesion (vapor phase)

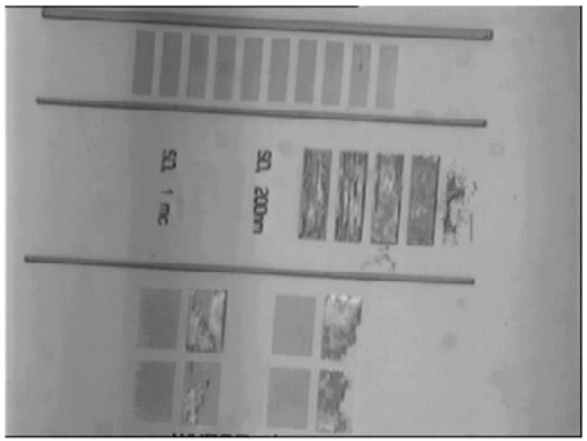


Imprinted lines (fidelity)

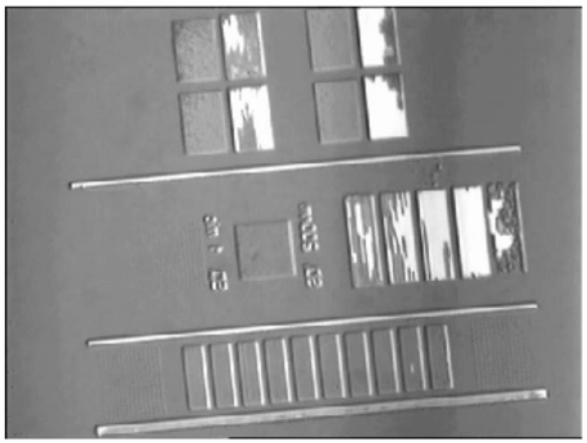


G.-Y. Jung *et al.*, *Langmuir* **21**, 1158 (2005).

Liquid phase

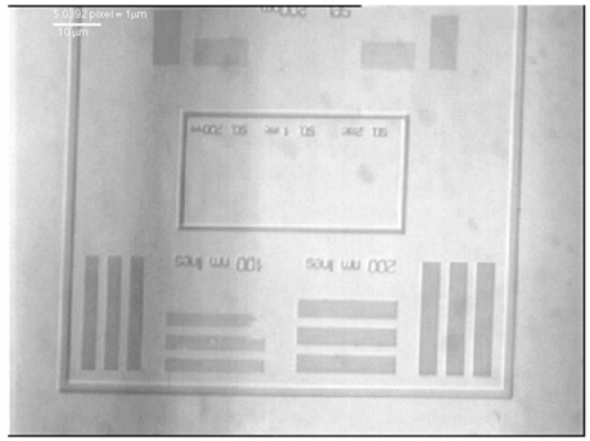


(a)

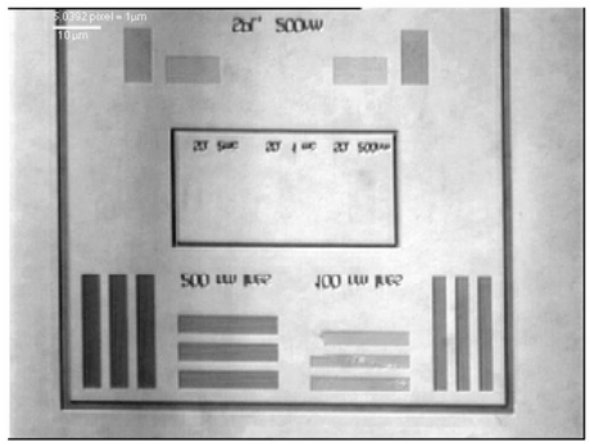


(b)

Vapor phase



(a)



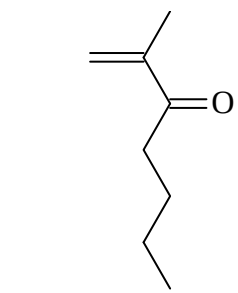
(b)

M . Beck *et al.*, *Microelectronic Engineering* **61– 62**, 441 (2002).

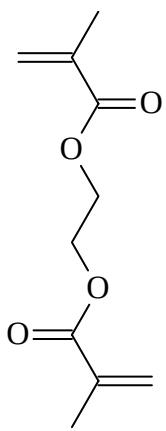
Application of C&HT

- Optimization of adhesion / release can be time-consuming, and quality control in nanoimprint is ill-defined and typically off-line
- High-throughput screening offers rapid assessment of new candidate materials and can define appropriate operating windows and tolerances:
  - new suppliers
  - new formulations
  - change in processing conditions

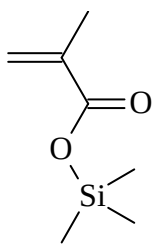
Model system



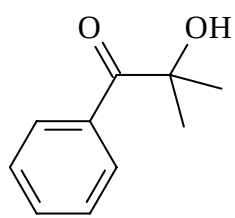
butyl methacrylate



ethylene glycol dimethacrylate



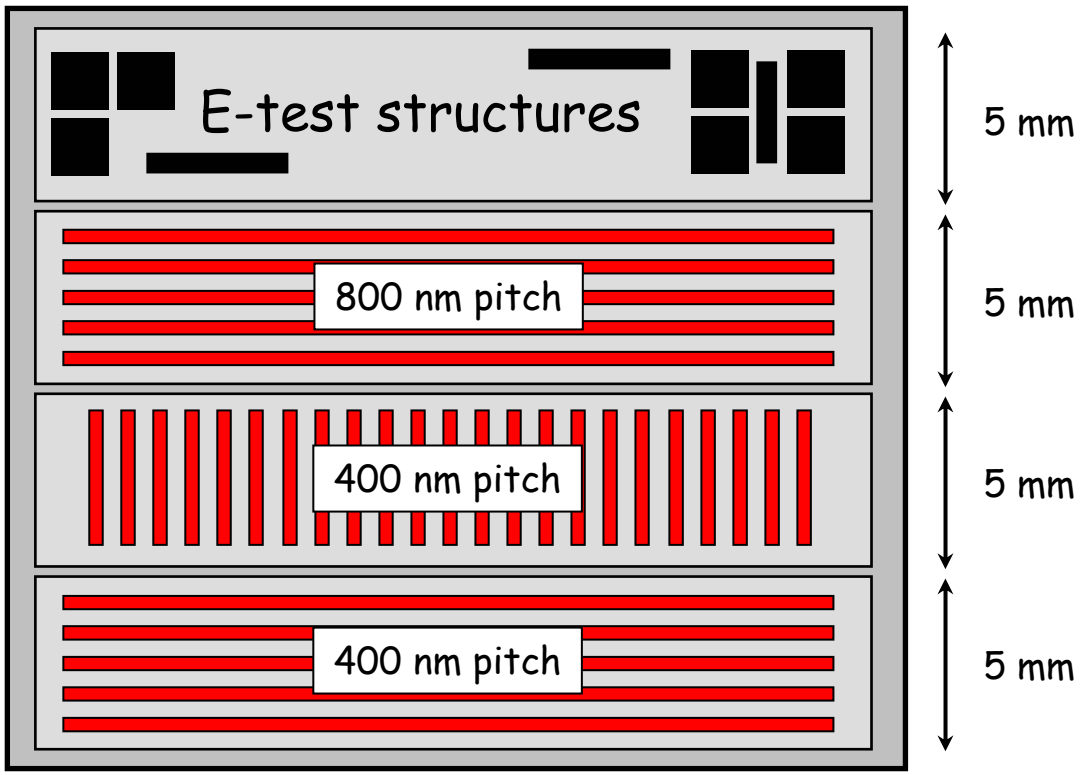
trimethylsilyl methacylate



Darocur 1173

Recipe from: M .D. Dickey *et al.*, *AICHE Journal* **51**, 2547 (2005).

Imprint Mold

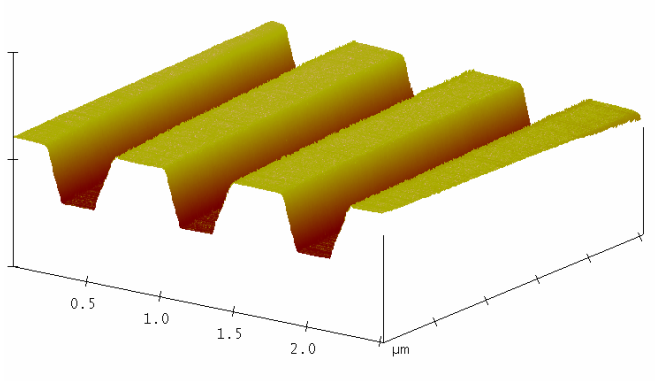


Height – 400 nm

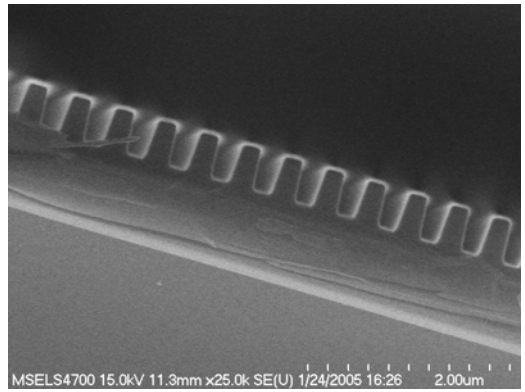
* Courtesy of Intel

Imprint Mold

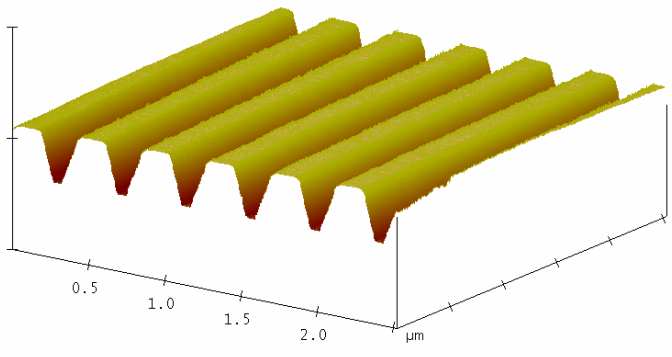
800 nm pitch



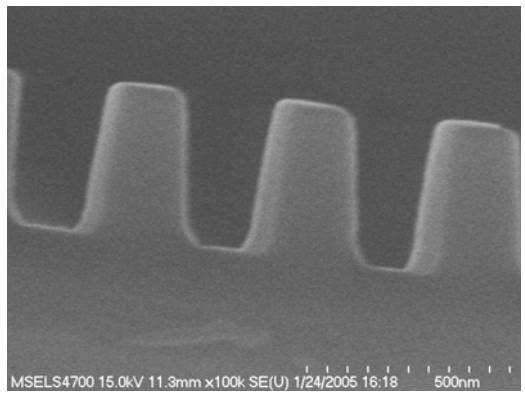
pitch (AFM) – 800 nm
height (AFM) – 403 nm



400 nm pitch

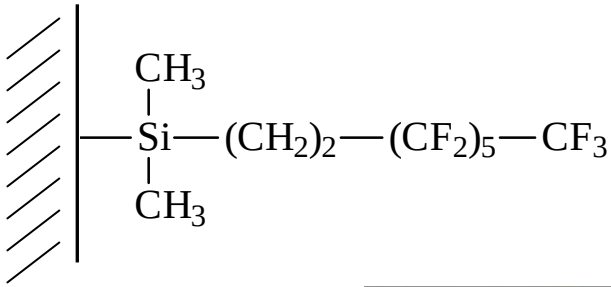


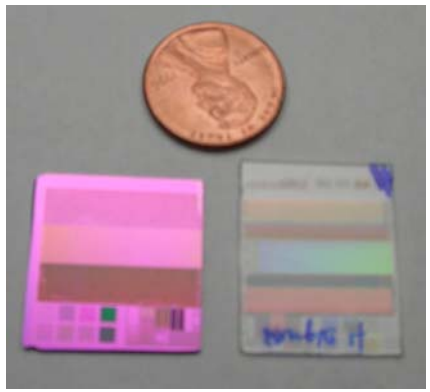
pitch (AFM) – 415 nm
height (AFM) – 354 nm



AFM likely not reaching bottom of pattern

Low γ Mold





flat silicon

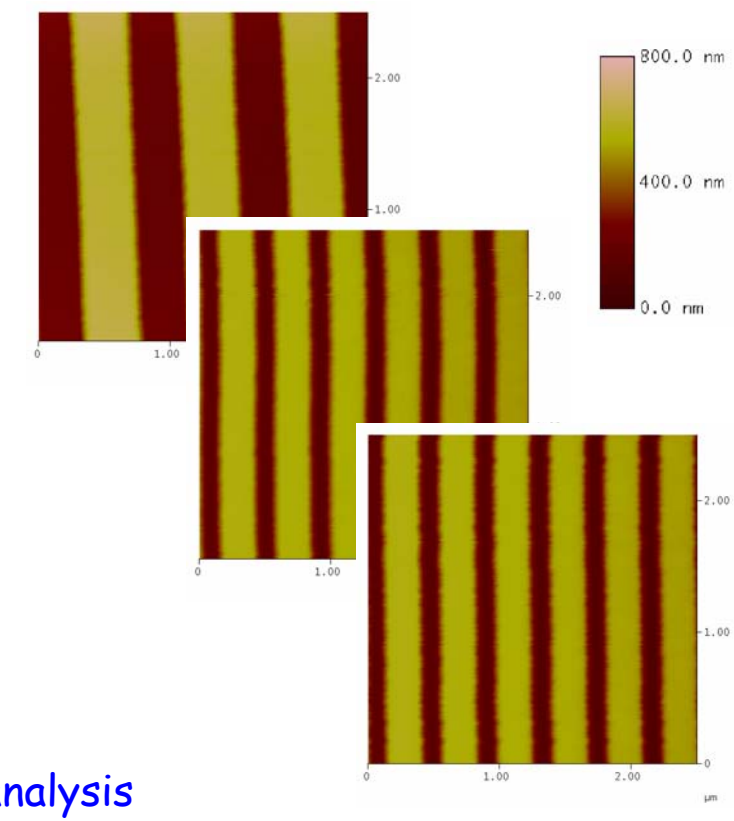
θ_A/θ_R = 111/95

mold

θ_A/θ_R = 150/129 (800 nm pitch)

θ_A/θ_R = 151/141 (400 nm pitch)

AFM of imprinted material

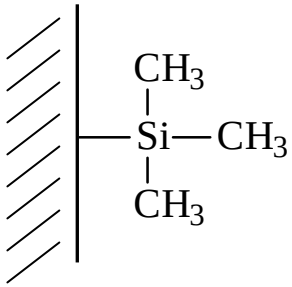


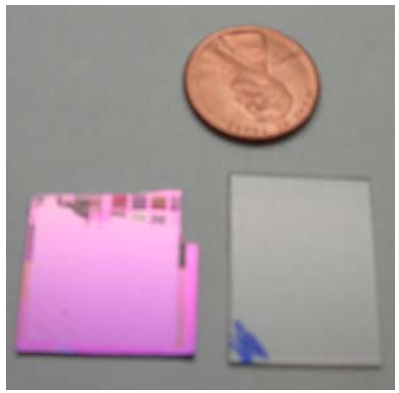
AFM analysis

	1	mold	2	3	mold
pitch	801	800	418	418	415
height	393	403	388	389	354

Intermediate γ Molds

NIST
National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce





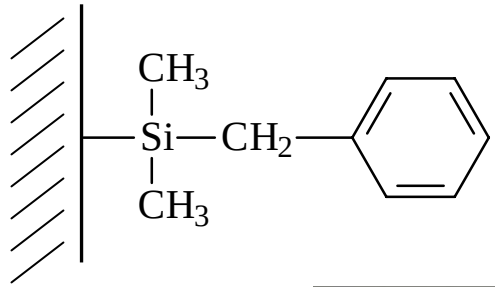
[flat silicon]

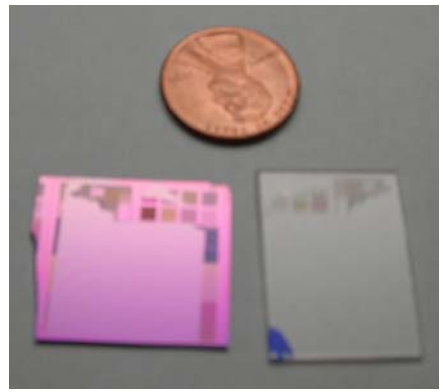
θ_A/θ_R = 93/79

[mold]

θ_A/θ_R = 150/pins (800 nm pitch)

θ_A/θ_R = 149/pins (400 nm pitch)





[flat silicon]

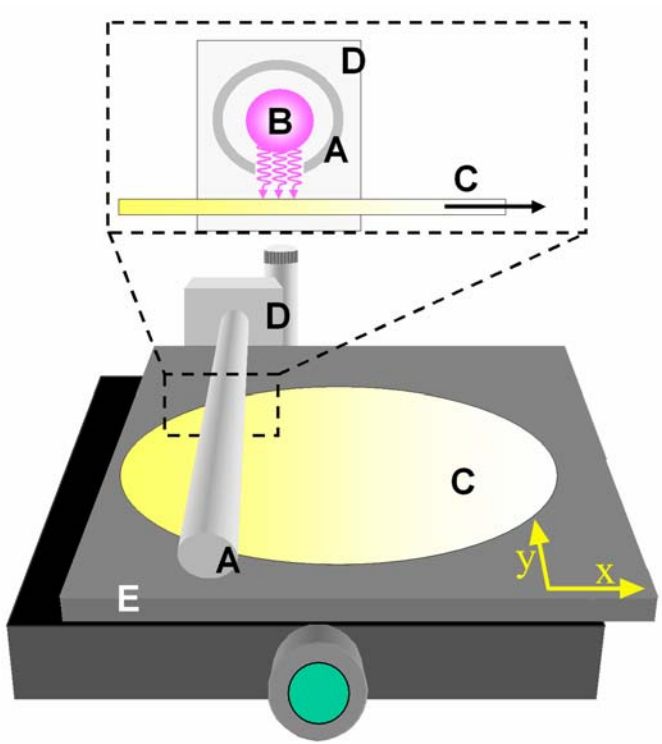
θ_A/θ_R = 79/57

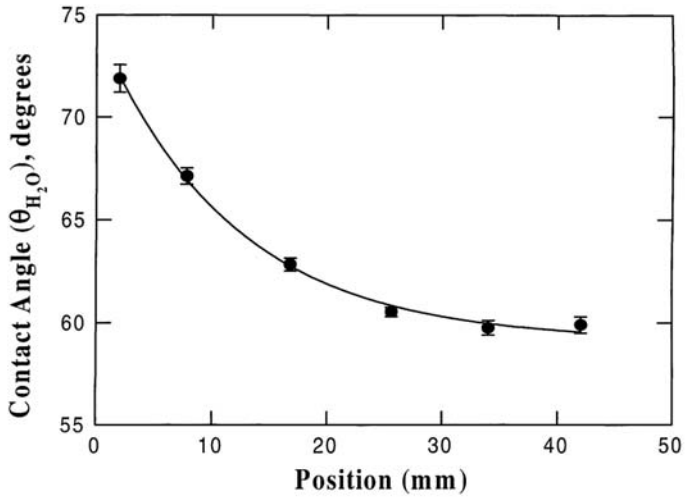
[mold]

θ_A/θ_R = 148/pins (800 nm pitch)

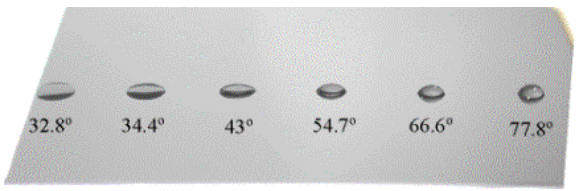
θ_A/θ_R = 148/pins (400 nm pitch)

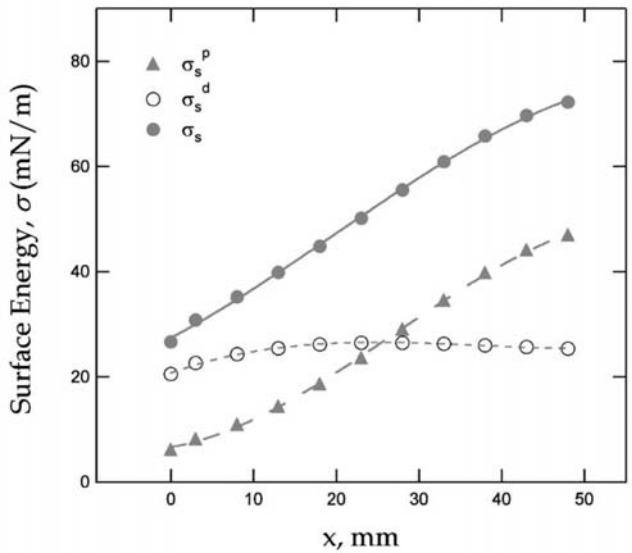
Surface Energy Gradients





Automated contact ∠ measurements





A. Sehgal, A. Karim, C.M. Stafford, M.J. Fasolka, *Microscopy Today* **11**, 26 (2003).

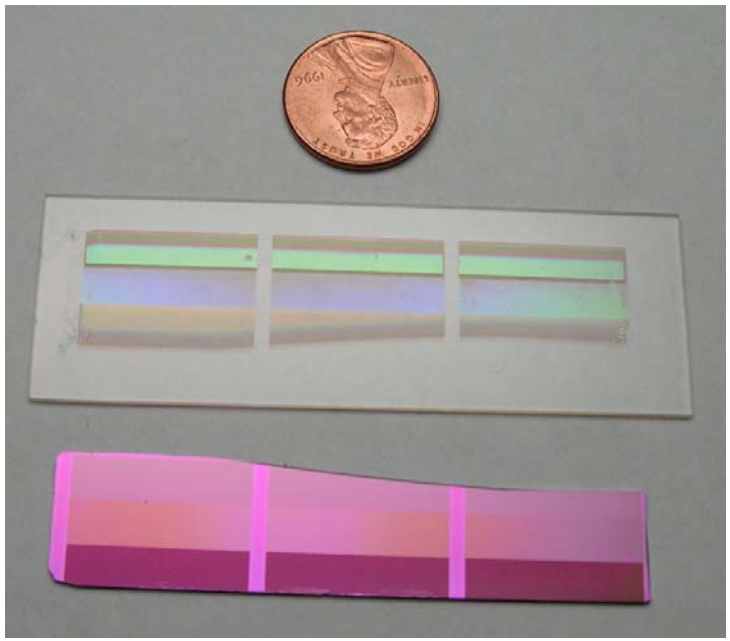
Surface Energy Gradient #1

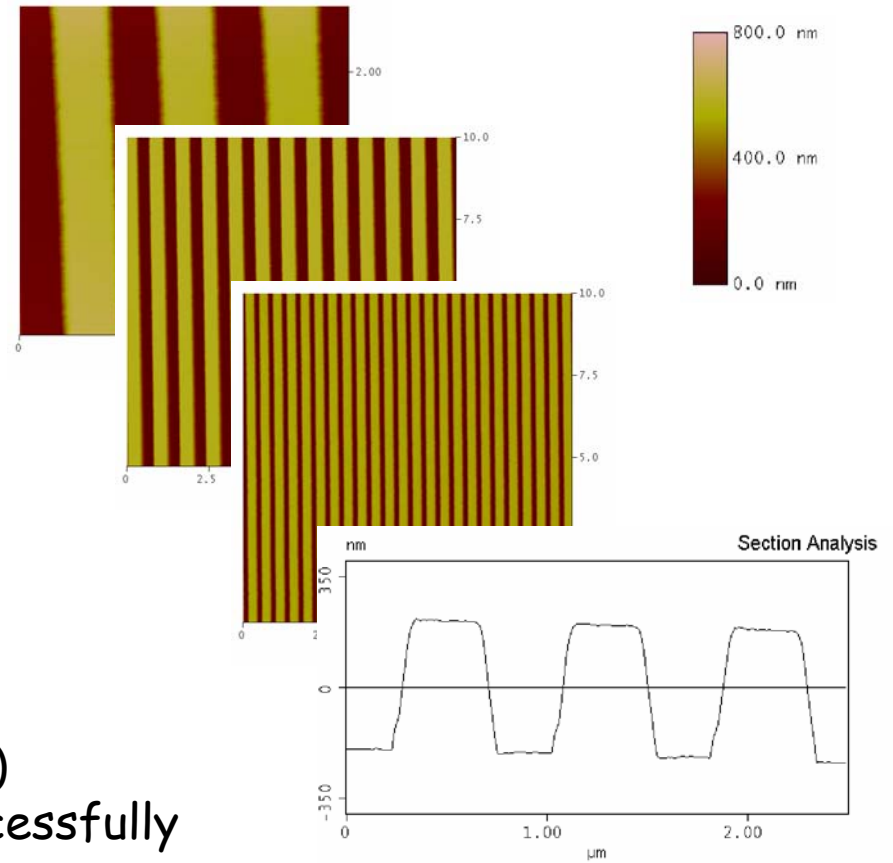
Zone 1 virgin	Zone 2 1 sec	Zone 3 3 sec	Zone 4 4 sec	Zone 5 5 sec	Zone 6 6 sec	virgin

step size – 0.1 mm

Zone	1	2	3	4	5	6
θ_A/θ_R	146/127	146/125	143/119	140/116	137/109	-

Surface Energy Gradient #1





- Gradient is shallow (high-resolution)
- All zones transferred patterns successfully

	mold	1	2	3	4	5	6
pitch	800	801	796	796	801	791	796
height	403	393	402	421	378	392	406

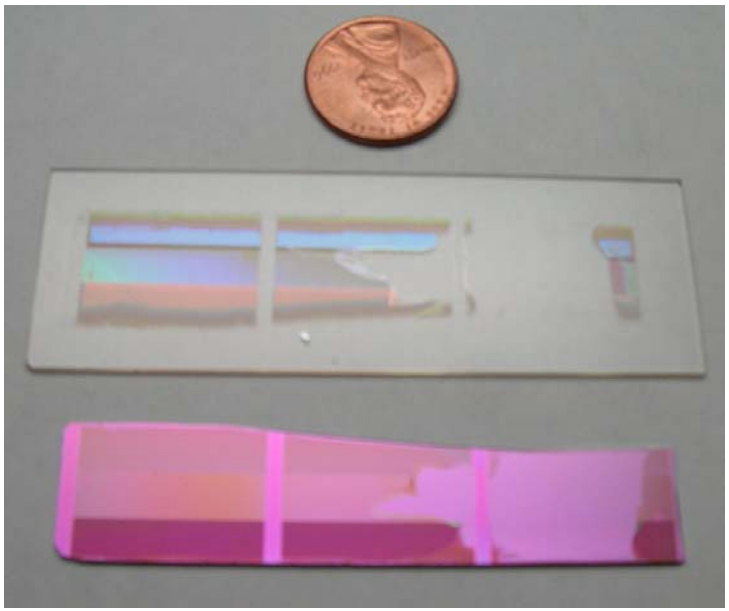
Surface Energy Gradient #2

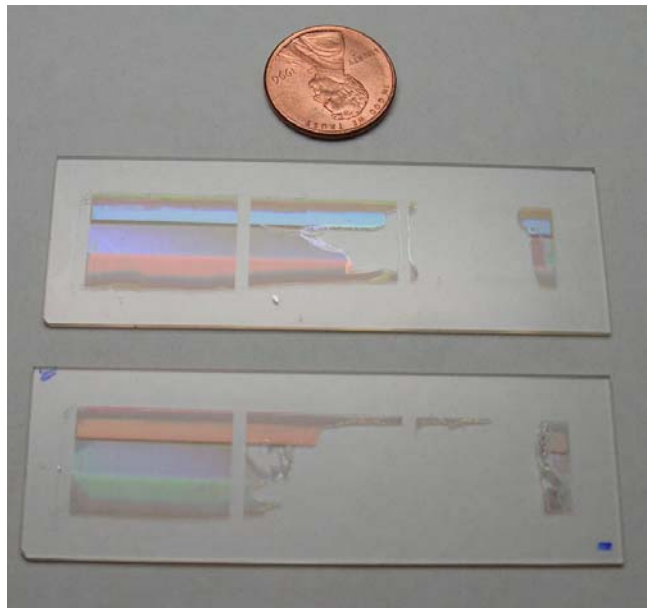
Zone 1 virgin	Zone 2 2 sec	Zone 3 4 sec	Zone 4 6 sec	Zone 5 8 sec	Zone 6 10 sec	virgin

step size – 0.1 mm

Zone	1	2	3	4	5	6
θ_A/θ_R	145/127	145/101	102/pins	81/pins	53/pins	wets

Surface Energy Gradient #2





- Gradient is steep (low-resolution)
- Failure occurs in Zone 4 (~θ_A=100)

- Repeat experiment
- Again, failure occurs in ~ Zone 4

Smaller pitch size (higher surface area) fails sooner.

Conclusions

- Adhesion & release in UV-NIL is highly dependent on surface chemistry
- C&HT methods can accelerate R&D as well as provide operation windows for QC
- Simple inspection yields qualitative measure of adhesion & release

Future Work

- Conduct more high-resolution surface energy gradients ($\theta_A \approx$ 150-100)
- Modify γ_{r-s} using methacryloxypropyl-type silane coupling agents
- Use wedge test to quantify adhesion energy (G_c) (SURF 2006).

Acknowledgments

- Brian Berry – UVO treatments
- Kate Hollabaugh – SURF student
- Susan Barnes – digital pictures