Nayudamma Memorial Lecture @ CLRI

Delights of Doing Research: Some Personal Lessons from Translational Sciences

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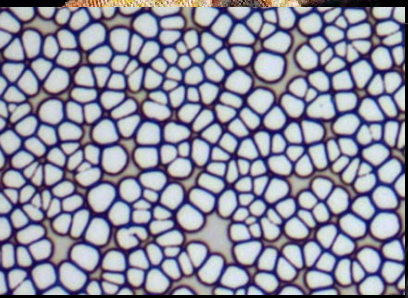
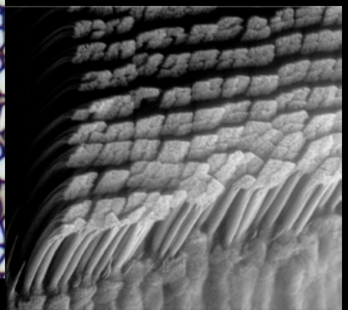
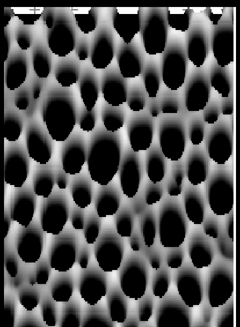
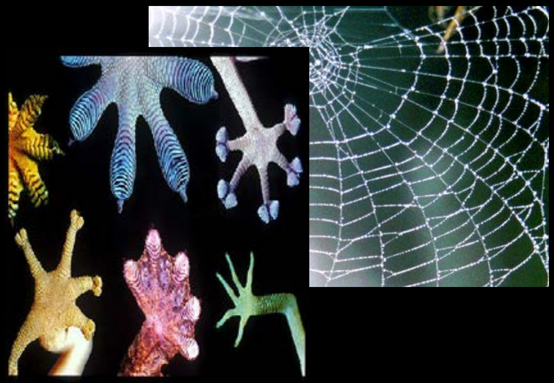



Research Themes

Meso 3M: Mechanics, Materials and Manufacturing

- Nano-mechanics: Instabilities, self-organization and pattern formation
- Micro/nano-fabrication and patterning of soft materials
- Textured Functional Interfaces: adhesive, wetting, optical……………..

- Nanomaterials for health, environment & energy…..
- MEMS, NEMS, Microfluidics, Sensors……….
- Micro/nano fibers and devices: Carbon-MEMS.
- Electrospinning of functional materials….

Some ABCs to ponder:

- ✓**(A) Moving away from incremental: High Risk/High gain!**
- ✓**(B) The power of lateral thinking, creativity and even common sense in solving scientific problems (do NOT follow the leader!).**
- ✓**(C) Translating scientific ideas/research to tangible technology for the societal needs.**
- ✓**(D) Innovation: Closing the sustainable knowledge circle……**

1. **Scientific Common Sense & Creativity: Connecting dots….**

2. **Problem-centric vs. Toolbox-centric Approaches to Research**

Multidimensionality of Key S &T sectors:

Energy, Water, Health, Environment, Food, Manufacturing, Information, Connectivity, Sustainable Habitats, Security……….

3. **Technology-centric vs. People-centric Worldviews**

"In the sky, there is no distinction of east and west; people create distinctions out of their own minds and then believe them to be true." -- Buddha

Molecular Self-assembly: 1 nm-100 nm (Chemistry)

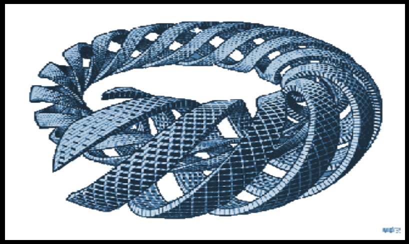
Self-organization: 1 micron-100 micron (Physics)

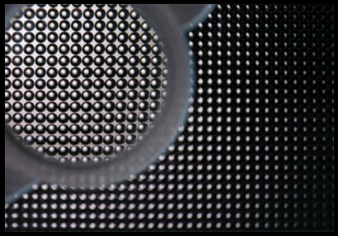
Self-organized Pattern Formation in Ultrathin (< 100 nm) Unstable Polymer Liquid Films

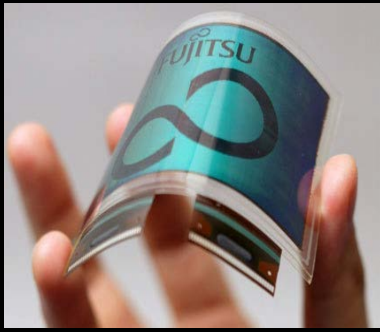
What limits it?

What is the use?

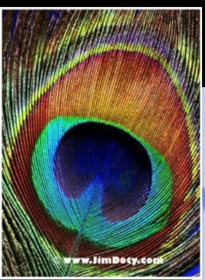
Large Area, Rapid Inexpensive
Micro or Nano Patterning Of Polymer Arrays:
Lenses, Sensors, devices…



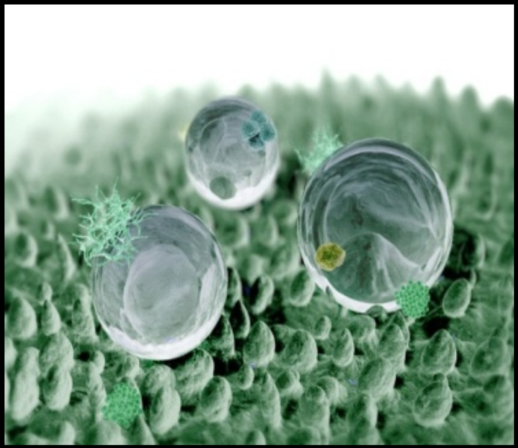




Nature-inspired Science: Micro/Nano Textured Functional Coatings for Control of Wetting, Adhesion and Color



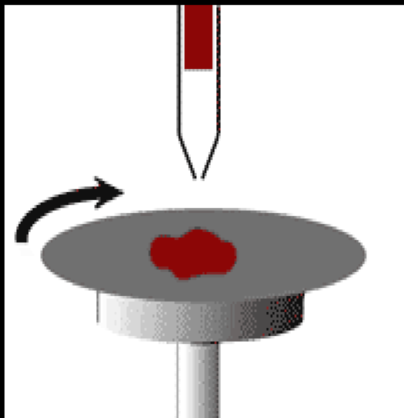
Structural colors: Photonic Crystals



Lotus effect: Self-clean water repellent surfaces

Reversible Bio-Adhesion: nano- velcro; Geckel glue

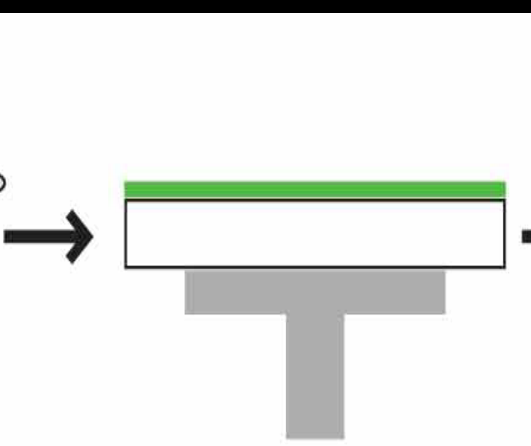
Self-organized Dewetting of Thin (< 100 nm) Polymer Films



Spin-coating of polymer solution

Heating above T_G or Exposure to solvent vapor

$$\lambda^2 \sim N^{-1} \sim \gamma / \phi \sim \text{(van der Waals) } H^4$$



(Quick) ABC of Thin Film Wetting

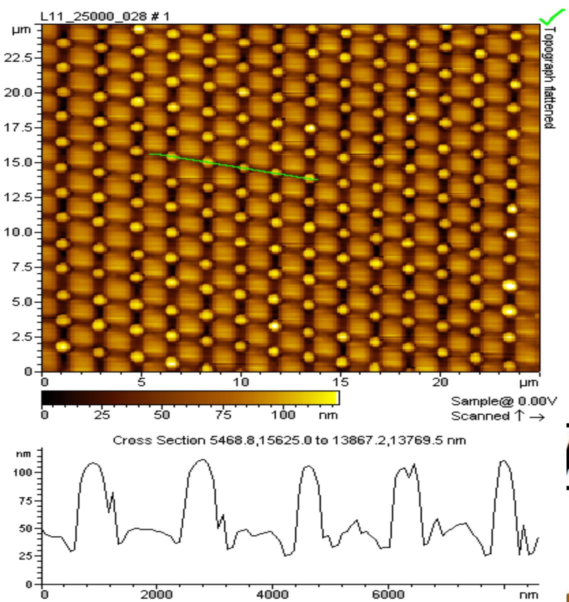
Why is it scientifically interesting?

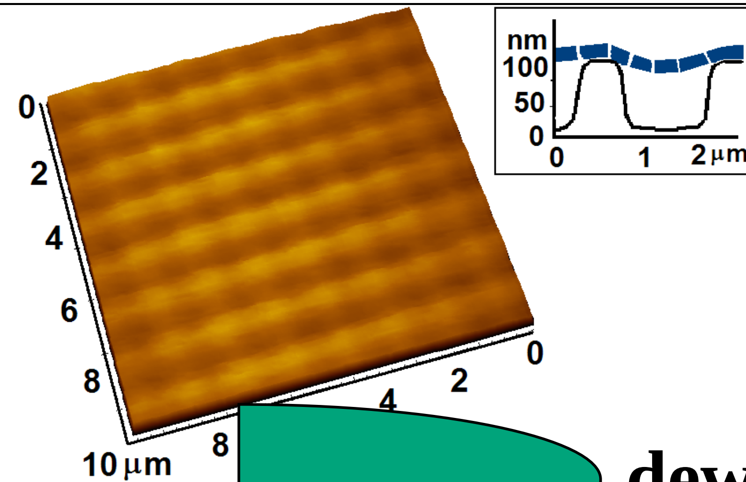
A workhorse for studies of:

Interfacial Science, Confinement,
Intersurface forces,
Micro-rheology, Surface instabilities,
Self-organization, Pattern formation,
Nucleation, Spinodal processes, adhesion,…….

Wetting is not just Science at Surfaces but goes much Deeper !

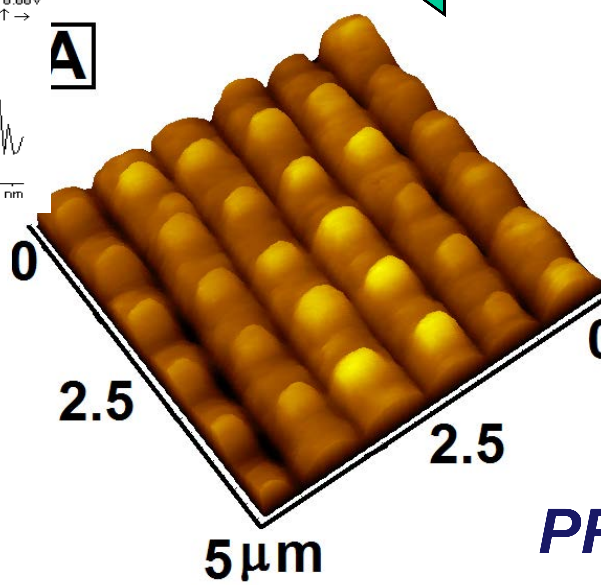
Ordered Structures by Dewetting on Physico-chemically Patterned Templates in Solvent Vapor or Heating

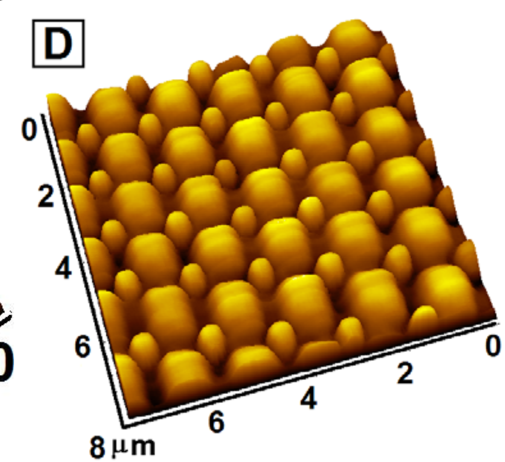


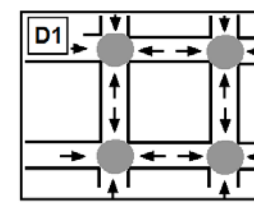


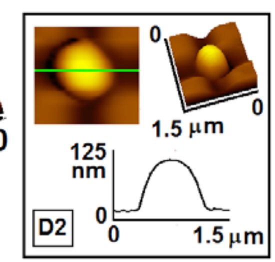
24 nm

dewetting









PRL 2001; Soft Matter 2008

Problems ??

1. Ultrathin film to be heated above Tg to allow mobility and then cooled…..(residual stresses)

2. Lateral feature size > several microns owing to:

A. Weak van der Waals destabilizing force
B. High surface tension stabilizing force
C. Low mobility; slow kinetics

3. Patterns with arbitrary, complex geometries and sharp corners are difficult to create by self-organization

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Four Problems, One Solution !!

Creativity is in the *Beginning*. Think Physical !

Integration of the equation of motion of the upper layer ($\mu_2 u_{2z} = \int P_{2x}\,dz$) leads to

$$\mu_2 u_{2z} = P_{2x} z + C_1 \quad \text{(iii)}$$

where P_2 is constant in the z direction.

At $z = h_2$, $\mu_2 u_{2z} = 0$. Therefore, from eq iii

$$C_1 = -P_{2x} h_2$$

Thus, eq iii can be modified to

$$\mu_2 u_{2z} = P_{2x} z - P_{2x} h_2 \quad \text{(iv)}$$

Integration of eq iv [$\mu_2 u_2 = \int (P_{2x} z - P_{2x} h_2)\,dz$] leads to

$$\mu_2 u_2 = P_{2x} z^2/2 - P_{2x} h_2 z + C_2 \quad \text{(v)}$$

At $z = h_1$, $u_2 = u_1$. Therefore, from eq v

$$C_2 = \mu_2 (u_1)_{h_1} - P_{2x}({h_1}^2/2) + P_{2x} h_2 h_1 \quad \text{(vi)}$$

$$\mu_2 u_2 = P_{2x}[(z^2 - {h_1}^2)/2] - P_{2x} h_2 (z - h_1) + \mu_2 (u_1)_{h_1} \quad \text{(vii)}$$

Integration of the equation of motion of the lower layer [$\mu_1 u_{1z} = \int P_{1x}\,dz$] leads to

$$\mu_1 u_{1z} = P_{1x} z + C_3 \quad \text{(viii)}$$

where P_1 is constant in the z direction.

At $z = h_1$, $\mu_2 u_{2z} = \mu_1 u_{1z}$. Therefore, eqs viii and iv simplify to

$$\mu_1 u_{1z} = P_{1x} z + (P_{2x} - P_{1x}) h_1 - P_{2x} h_2 \quad \text{(ix)}$$

Integration of eq ix {$\mu_1 u_1 = \int [P_{1x} z + (P_{2x} - P_{1x}) h_1 - P_{2x} h_2]\,dz$} leads to

$$\mu_1 u_1 = P_{1x}(z^2/2) + (P_{2x} - P_{1x}) h_1 z - P_{2x} h_2 z + C_4 \quad \text{(x)}$$

At $z = 0$, $u_1 = 0$. Therefore, eq x leads to $C_4 = 0$. Consequently

$$\mu_1 u_1 = P_{1x}(z^2/2) + (P_{2x} - P_{1x}) h_1 z - P_{2x} h_2 z \quad \text{(xi)}$$

Differentiation of eq xi with respect to x leads to

$$\mu_1 u_{1x} = P_{1xx}(z^2/2) + [(P_{2x} - P_{1x}) h_1]_x z - (P_{2x} h_2)_x z \quad \text{(xii)}$$

The equation of continuity ($u_{1x} + w_{1z} = 0$) and eq xii simplify to

$$-\mu_1 w_{1z} = P_{1xx}(z^2/2) + [(P_{2x} - P_{1x}) h_1]_x z - (P_{2x} h_2)_x z \quad \text{(xiii)}$$

Integrating eq xiii ($-\mu_1 w_{1z} = \int \{P_{1xx}(z^2/2) + [(P_{2x} - P_{1x}) h_1]_x z - (P_{2x} h_2)_x z\}\,dz$] gives

$$-\mu_1 w_1 = P_{1xx}(z^3/6) + [(P_{2x} - P_{1x}) h_1]_x (z^2/2) - (P_{2x} h_2)_x (z^2/2) + C_5 \quad \text{(xiv)}$$

At $z = 0$, $w_1 = 0$. Therefore, eq xiv leads to $C_5 = 0$ and

$$-\mu_1 w_1 = P_{1xx}(z^3/6) + [(P_{2x} - P_{1x}) h_1]_x (z^2/2) - (\mathbf{P}_{2x} h_2)_x (z^2/2) \quad \text{(xv)}$$

At height h_1, eqs xi and xv reduce to

$$(u_1)_{h_1} = (1/\mu_1)[P_{1x}({h_1}^2/2) + (P_{2x} - P_{1x}){h_1}^2 - P_{2x} h_2 h_1] \quad \text{(xvi)}$$

$$(w_1)_{h1} = (-1/\mu_1)\{P_{1xx}({h_1}^3/6) + [(P_{2x} - P_{1x}) h_1]_x ({h_1}^2/2) - (P_{2x} h_2)_x ({h_1}^2/2)\} \quad \text{(xvii)}$$

Substituting eqs xvi and xvii into eq i gives the final form of the kinematic condition for the liquid–liquid interface

$$\frac{\partial h_1}{\partial t} - \frac{1}{3\mu_1}\frac{\partial}{\partial x}\left({h_1}^3 \frac{\partial P_1}{\partial x}\right) + \frac{1}{2\mu_1}\frac{\partial}{\partial x}\left[{h_1}^2 (h_1 - h_2)\frac{\partial P_2}{\partial x}\right] = 0 \quad \text{(xviii)}$$

Equation vii can be written as follows

$$\mu_2 u_2 = P_{2x}[(z^2 - {h_1}^2)/2] - P_{2x} h_2 (z - h_1) + (\mu_2/\mu_1)[P_{1x}({h_1}^2/2) + (P_{2x} - P_{1x}){h_1}^2 - P_{2x} h_1 h_2] \quad \text{(xix)}$$

Differentiating eq xix with respect to x gives

$$u_{2x} = (1/\mu_2)[P_{2xx}(z^2/2) - (P_{2x}{h_1}^2/2)_x - (P_{2x} h_2)_x z + (P_{2x} h_2 h_1)_x] + (1/\mu_1)[(P_{2x}{h_1}^2)_x - (P_{2x} h_2 h_1)_x - (P_{1x}{h_1}^2/2)_x] \quad \text{(xx)}$$

Replacing u_{2x} from the equation of continuity $u_{2x} + w_{2z} = 0$ and then integrating eq xx leads to the following expression

$$-w_2 = (1/\mu_2)[P_{2xx}(z^3/6) - (P_{2x}{h_1}^2/2)_x z - (P_{2x} h_2)_x (z^2/2) + (P_{2x} h_2 h_1)_x z] + (1/\mu_1)[(P_{2x}{h_1}^2)_x - (P_{2x} h_2 h_1)_x - (P_{1x}{h_1}^2/2)_x] z + C_6 \quad \text{(xxi)}$$

At $z = h_1$, $w_2 = w_1$. Therefore, eq xxi gives the expression for constant C_6

$$C_6 = (1/\mu_1)\{P_{1xx}({h_1}^3/6) + P_{2xx}[(h_2{h_1}^2/2) - ({h_1}^3/2)] + P_{2x} h_{1x}(h_2 h_1 - 3{h_1}^2/2) + P_{1x} h_{1x}({h_1}^2/2) + P_{2x} h_{2x}({h_1}^2/2)\} - (1/\mu_2)\{P_{2xx}[(-{h_1}^3/3) + (h_2{h_1}^2/2)] + P_{2x} h_{1x}(h_1 h_2 - {h_1}^2) + P_{2x} h_{2x}({h_1}^2/2)\} \quad \text{(xxii)}$$

Equation xix is evaluated at height h_2

$$(u_2)_{h_2} = (1/\mu_2)\{P_{2x}[({h_2}^2 - {h_1}^2)/2] - P_{2x} h_2 (h_2 - h_1)\} + (1/\mu_1)[-P_{1x}({h_1}^2/2) + P_{2x}{h_1}^2 - P_{2x} h_1 h_2] \quad \text{(xxiii)}$$

Equations xxii and xxi lead to the following expression for w_1 at height h_2

$$-(w_2)_{h2} = (1/\mu_2)\{(P_{2xx}/3)(h_1 - h_2)^3 + P_{2x} h_{1x}(h_1 - h_2)^2 + P_{2x} h_{2x}[h_1 h_2 - ({h_1}^2/2) - ({h_2}^2/2)]\} + (1/\mu_1)\{P_{2xx}[(-{h_1}^3/2) + (3{h_1}^2 h_2/2) - {h_2}^2 h_1] + P_{1xx}[({h_1}^3/6) - ({h_1}^2 h_2/2)] + P_{2x} h_{2x}[({h_1}^2/2) - h_1 h_2] + P_{2x} h_{1x}(3h_1 h_2 - {h_2}^2 - 3{h_1}^2/2) + P_{1x} h_{1x}[({h_1}^2/2) - h_1 h_2]\} \quad \text{(xxiv)}$$

Substituting eqs xxiii and xxiv into eq ii gives the final

Many Problems, One Intuitive Solution !!

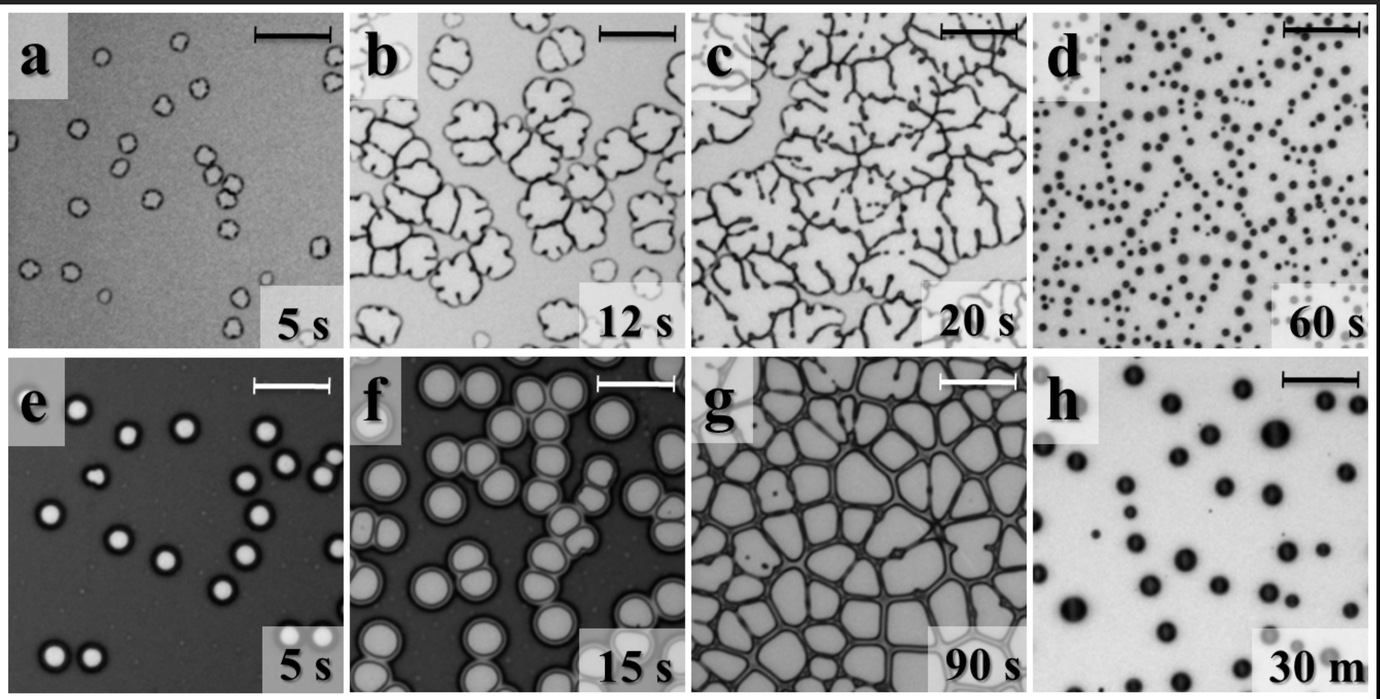
Dewetting under a Magic Mix of liquids

(Mixture of a solvent and a non-solvent):

[MEK, Water, and Acetone (15:7:3)]

a) **Polymer cannot dissolve in the mixture**
b) **Glass transition goes below room temperature; liquid polymer at room temp**
c) **Interfacial tension becomes very small**
d) **Destabilizing forces may get stronger**
e) **Residual stresses get weaker**

Pushing the Limits of Self-organization Down to sub- 100 nm

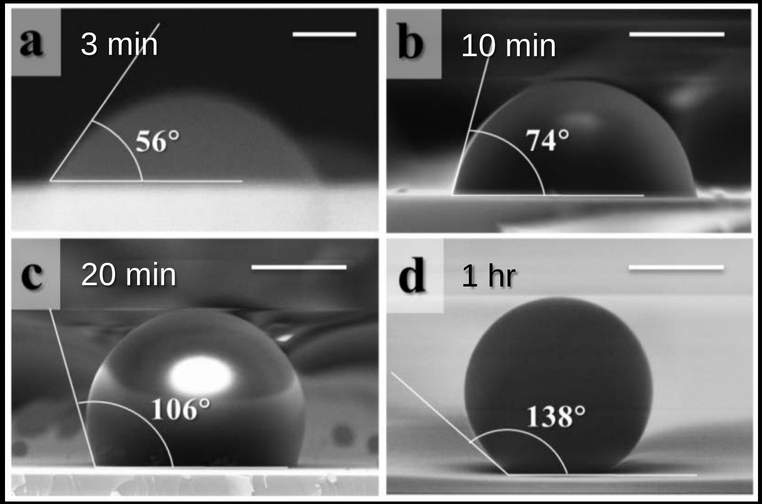


18 nm

Scale bar: 10 µm

60 nm

Tunable Nano -lenses



Dewetting time in air ~ 10 minutes (18 nm), 6 hours (60 nm).

FASTER & FINER DEWETTING UNDER WATER-ORGANIC MIX

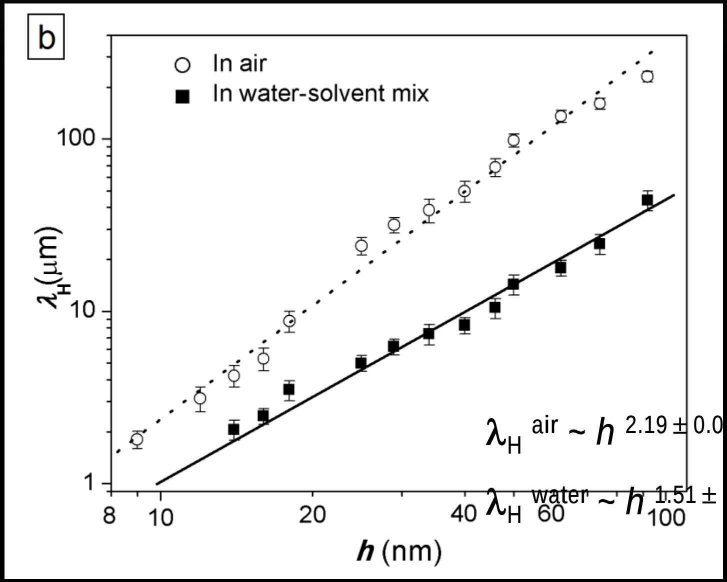
Water, MEK and acetone (15:7:3).

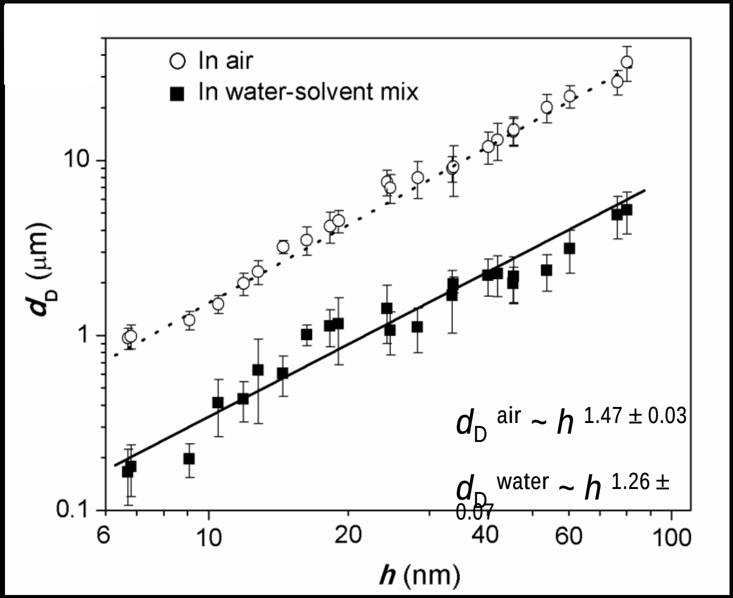
Advanced Materials 2010

Scale bar: 500 nm

ENHANCED DEWETTING: PATTERN LENGTH SCALES

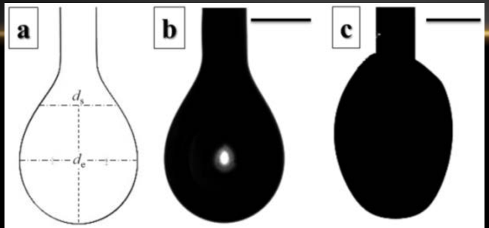
- ✓ Surface tension decreases from 25.8 to 0.55 mN/m
- ✓ van der Waals force replaced by stronger electrostatic attraction; U ~ 36 mV





$$\lambda_{vw} = 4\pi\sqrt{\frac{\pi\gamma}{A_e}}h^2 \quad \rightarrow A_e = 1.8 \times 10^{-20}\ \mathrm{J}$$

$$\lambda_{el} = \frac{2\pi}{U}\sqrt{\frac{2\gamma}{\epsilon\epsilon_o}}h^{1.5} \quad \rightarrow U = 36\ \mathrm{mV}$$



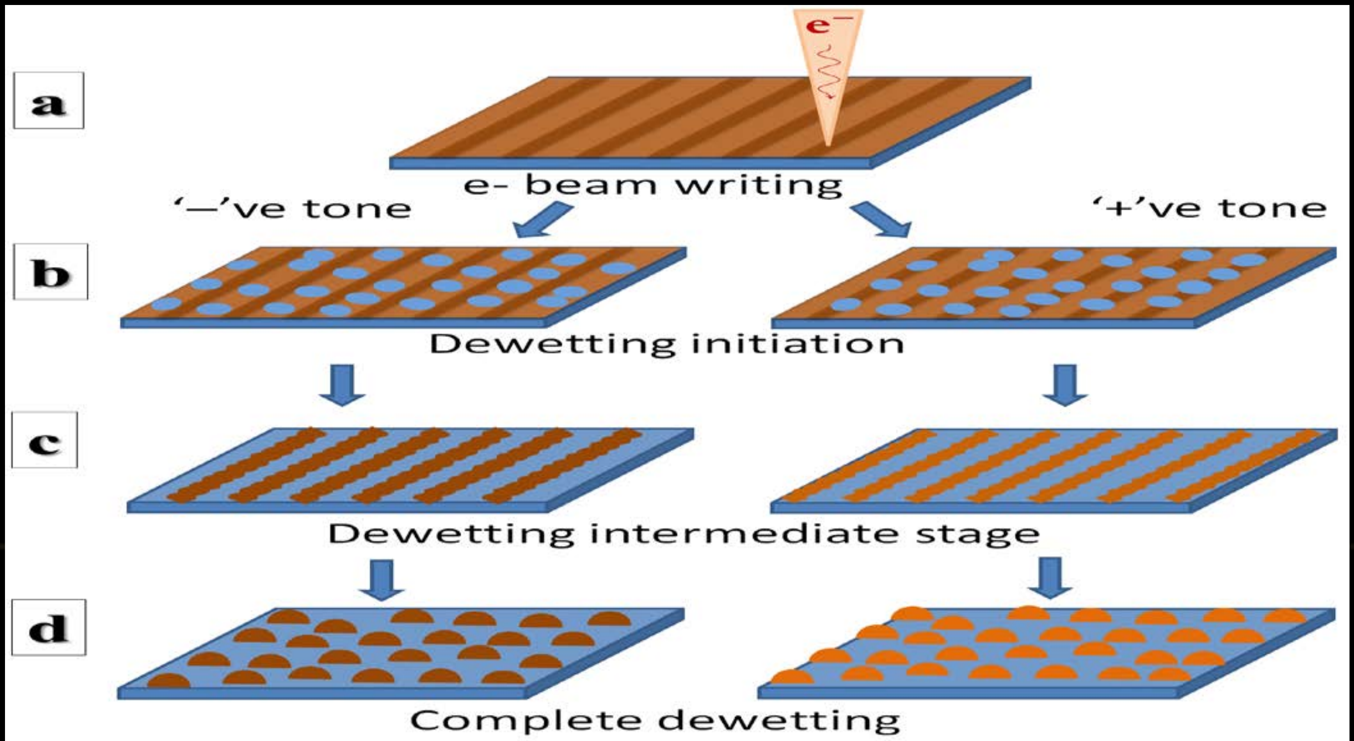
Macromolecules 2011

E-BEAM ASSISTED ORDERED DEWETTING

- Short e-beam exposure increases (decreases) the effective viscosity of negative (positive) tone e-beam resist.

  PS: negative tone (increased viscosity);
  PMMA : positive tone (decreased viscosity)

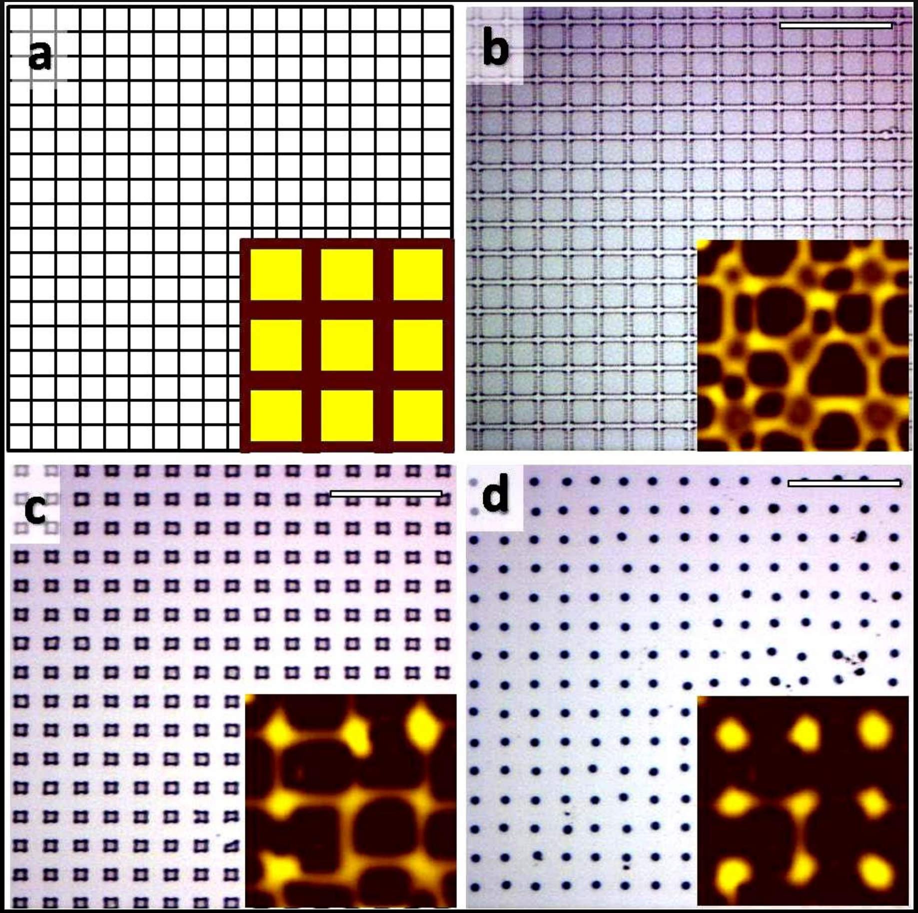
- Dewetting initiates and grow faster in the low viscous regions and leads to the ordered array of Nano-lenses.



EVOLUTION OF SQUARE GRID PATTERN: BEST FIDELITY

- 17 nm PMMA film
- Single pixel square grid at 6 μm periodicity, dwell time of 10 kV e-beam is 500 ns.
- Viscosity ratio in the exposed and unexposed regions: 0.01
- The inset images show simulated spatiotemporal evolution of instability

E-beam exposure pattern Square fluid domains!!

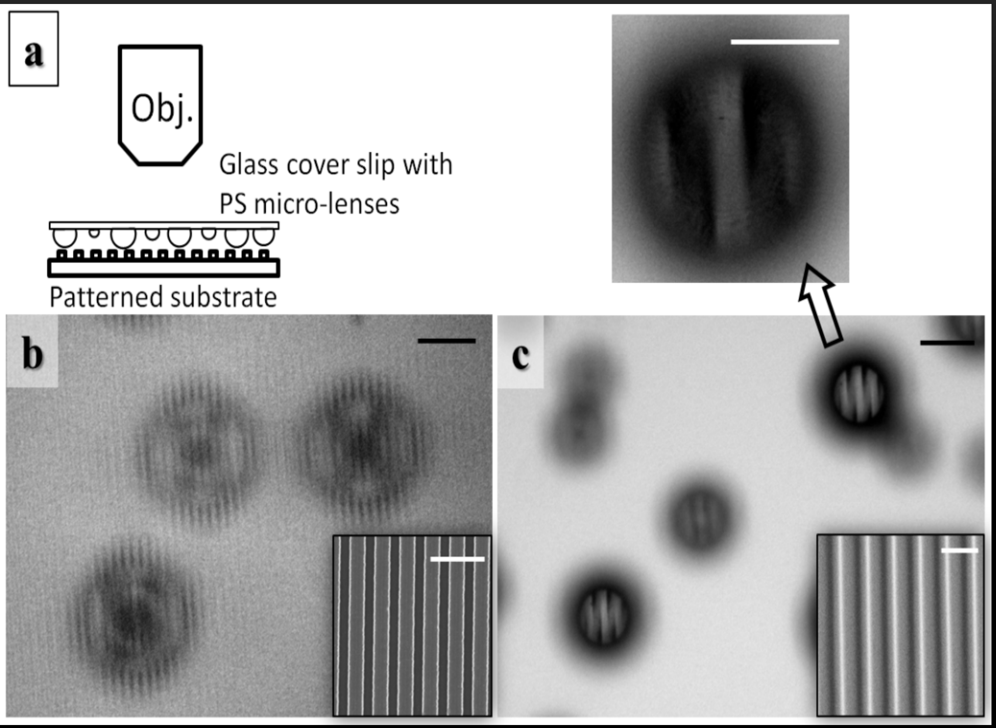


Square fluid domains!! **Rounding off…..**

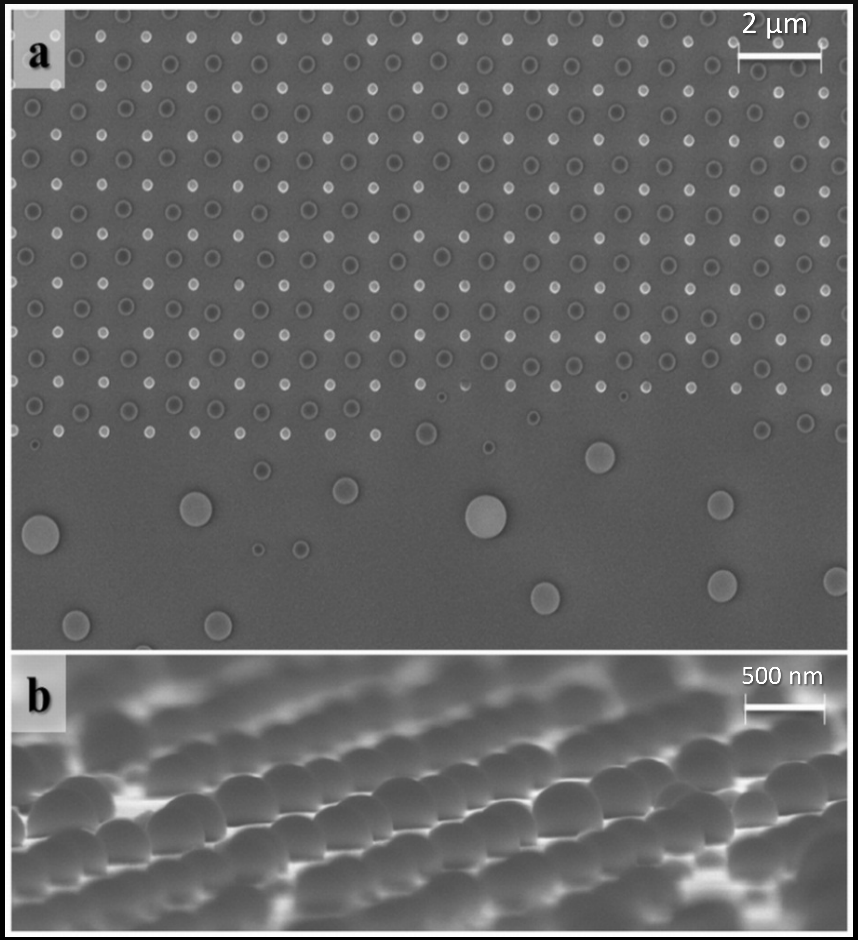
Macromolecules 2015

Scale bar: 20 μm

SUB-MICROMETER LENS ARRAYS BY DEWETTING



Template/e-beam assisted

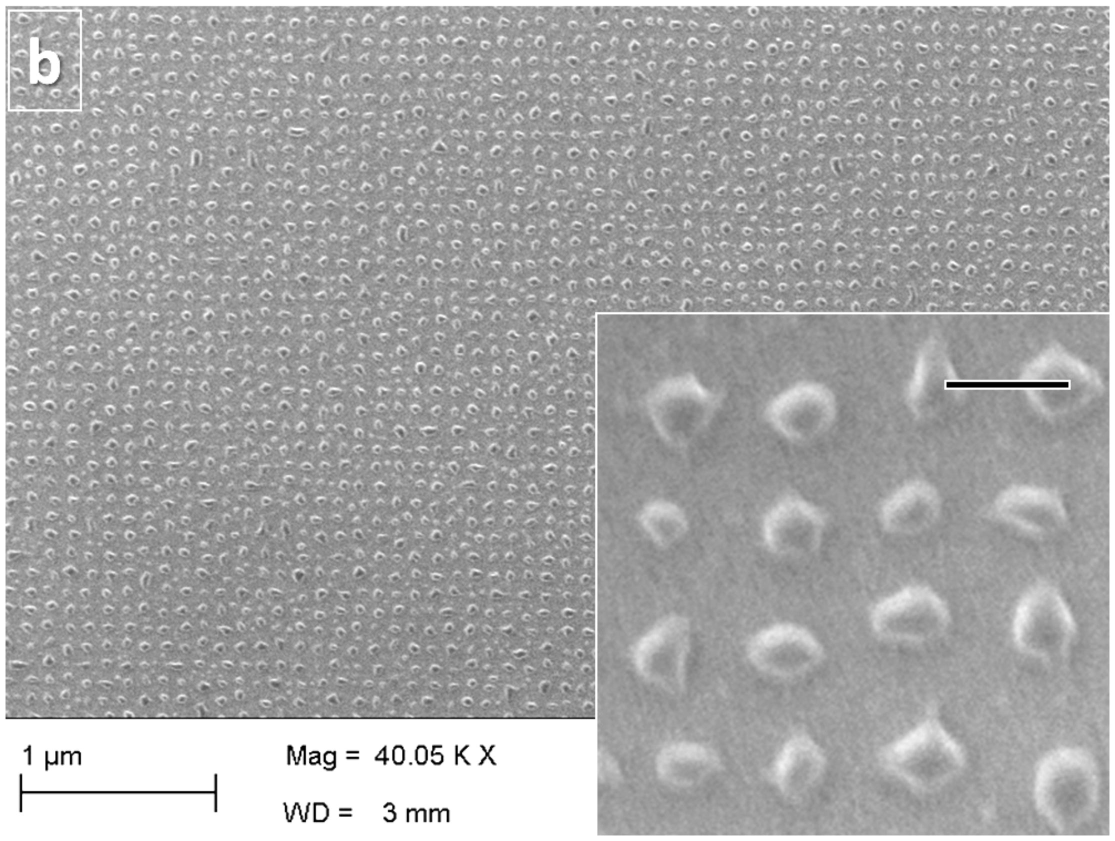


700 nm line spacing
20 nm thick PS film
beam dose ~ 100 μC/cm^2

Advanced Materials 2010; Macromolecules 2011; Soft Matter 2011

LIMITS OF SELF-ORGANIZATION; WHERE PHYSICAL SELF-ORGANIZATION MEETS CHEMICAL SELF-ASSEMBLY : SUB-40 NM ARRAY OF NANO-DOMAINS/LENSES

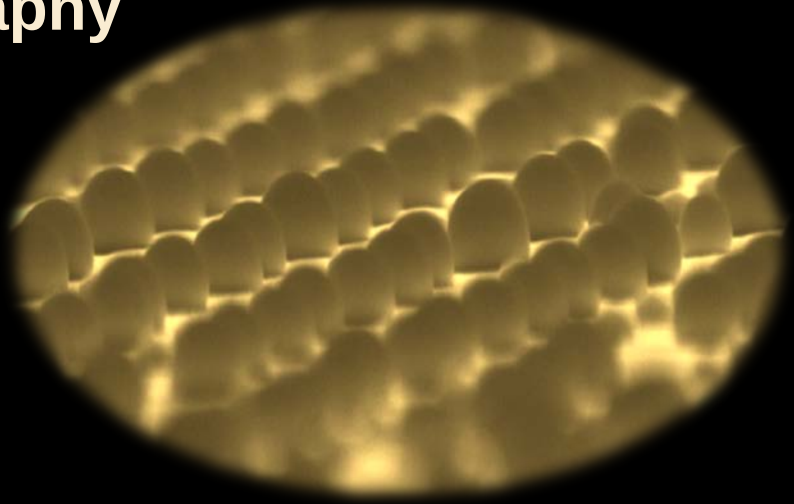
- ~35 nm size nano-dots in a 100 nm square array.
- Fabricated by the dewetting of 5.2 nm thick PS film.
- ~ 10 molecules/dot !



Scale bar: 100 nm

Micro/Nano Lens Arrays

- ✓ Opto-electronics, CCD arrays, digital projectors, photovoltaics……
- ✓ Signal enhancement (Raman spectroscopy?)
- ✓ Compound eye (fast motion detection; low light….)
- ✓ Near-field detection of low intensity optical signals.
- ✓ Compound mask for photolithography/selective deposition
- ✓ **Micro-lens Projection lithography**



http://www.flickriver.com/photos/opoterser/3085177911/

What do we look in a fabrication technique?

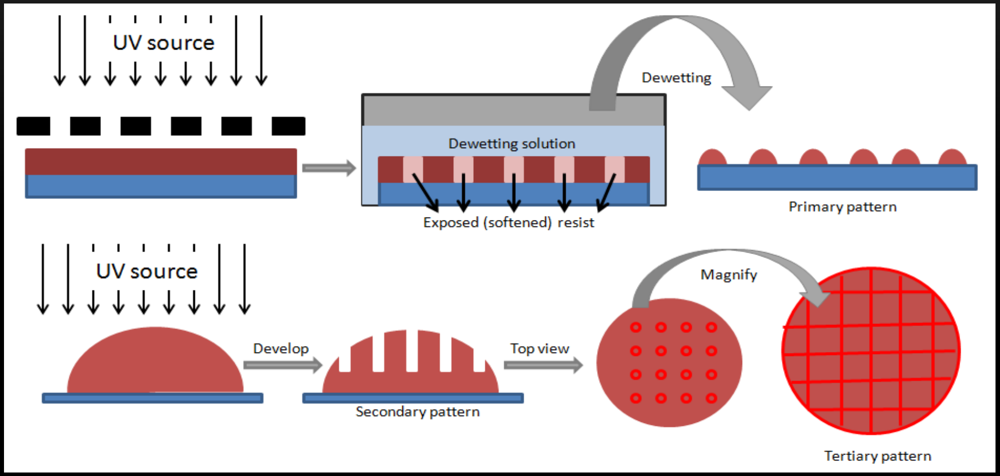
Portability, Portability, Portability (across)……

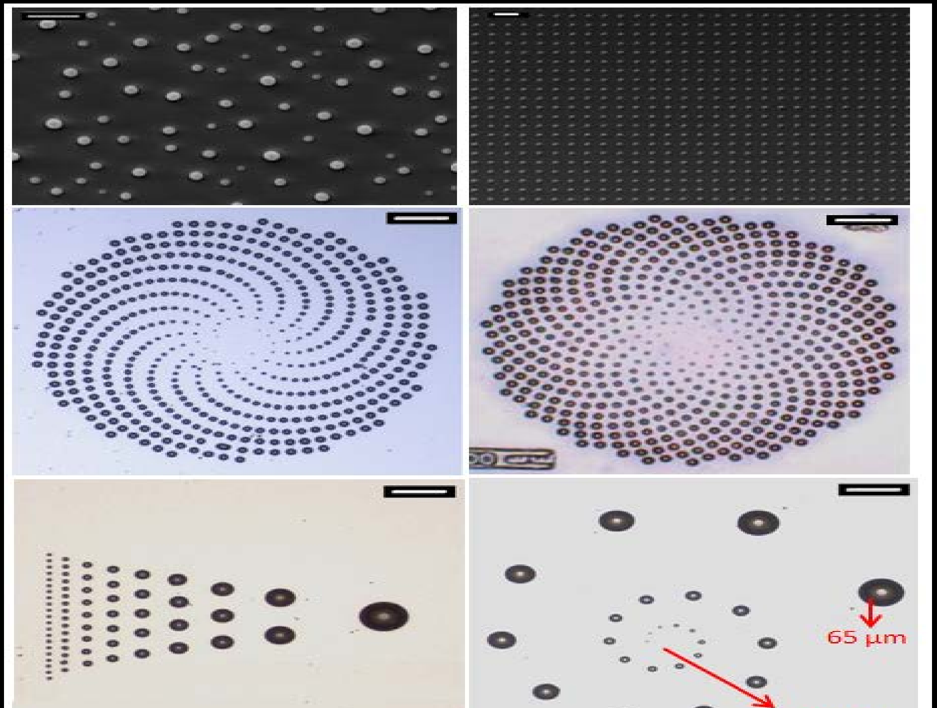
A. Materials (functional polymers; chalcogenides; polymer nanocomposites; photoresists; ……)

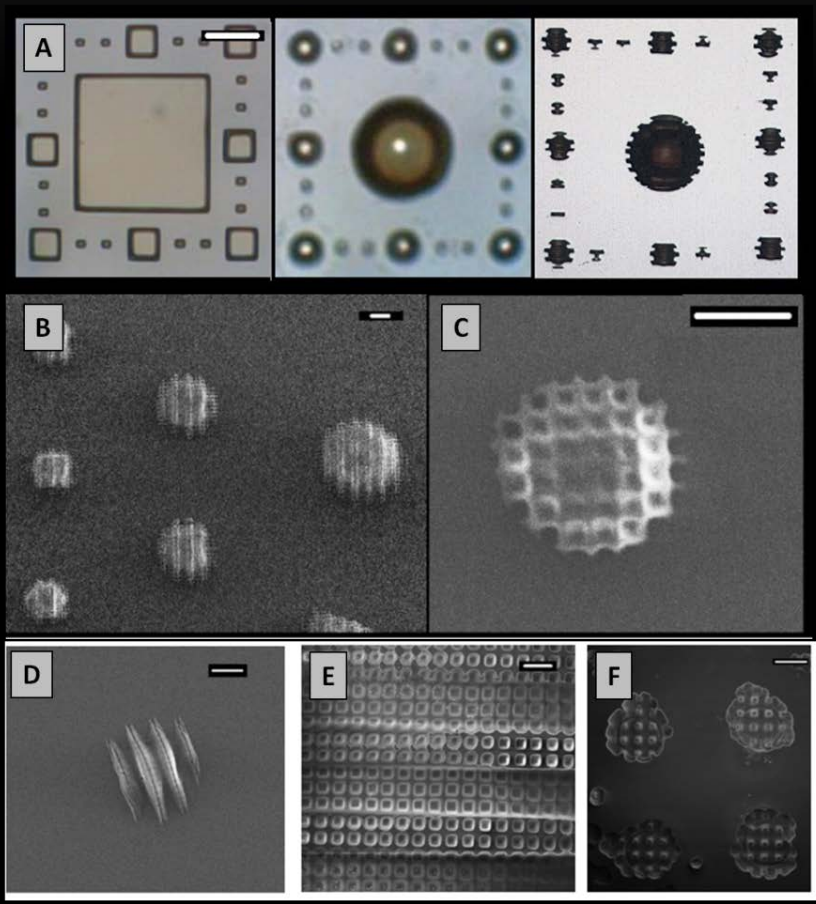
B. Synergy with common top-down tools; Methods of pre-patterns (e-beam; UV; laser; photo-patterning; …..)

C. Geometries (complex; hierarchical, three dimensional; fractal….)

Geometries: Hierarchical, three dimensional microstructures by Photoresist Dewetting and Photopatterning

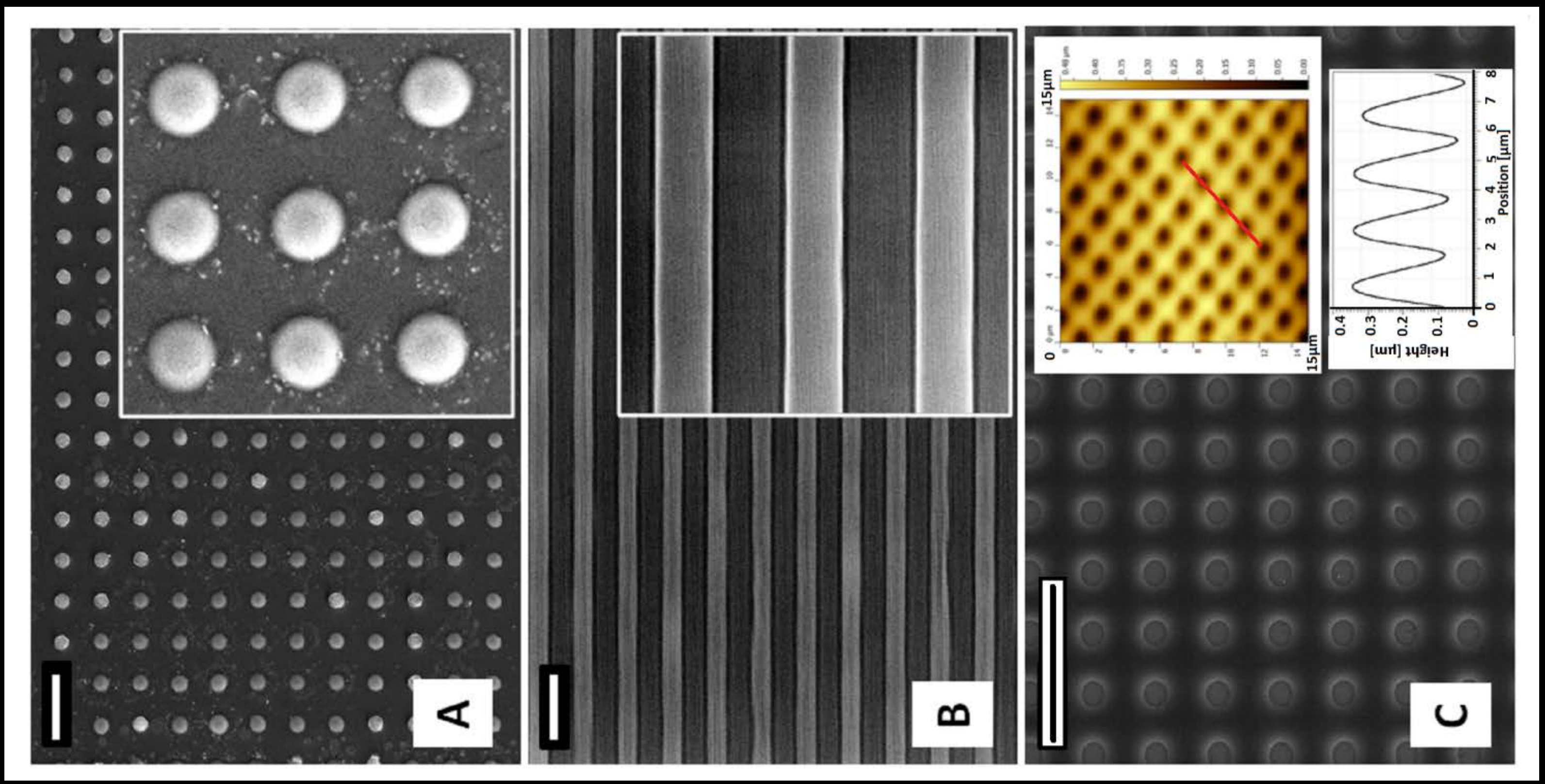






10 µm bar

Functional Materials: Amorphous Chalcogenide Arsenic Selenide (As_2Se_3) Micro Lenses and Gratings for IR Optics



Random Thoughts on the Road to Obvious Strike again!

- When a distinguished but elderly scientist states that something is possible, he is almost certainly right. When he states that something is impossible, he is very probably wrong.
- The only way of discovering the limits of the possible is to venture a little way past them into the impossible.
- "Believe nothing, no matter where you read it or who said it, no matter if I have said it, unless it agrees with your own reason and your own common sense…."---Buddha

Where and *How* we focus? It really matters !!

1. Seeing is believing, yes,
but what is *seeing* ?

[Story of STM, AFM: Gerd Binnig and Heinrich Rohrer at IBM Zurich in 1981; the Nobel prize in physics in 1986.]

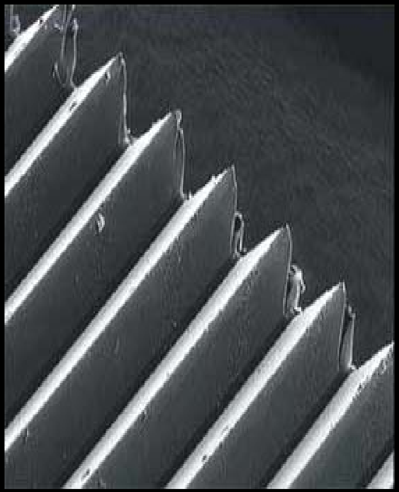
2. What we retain is good, but what we discard may be far more important !!

[Story of graphene—single layer of C atoms:

Andre Geim & Konstantin Novoselov ;
the Nobel prize in physics in 2010]

Serendipity does really work,

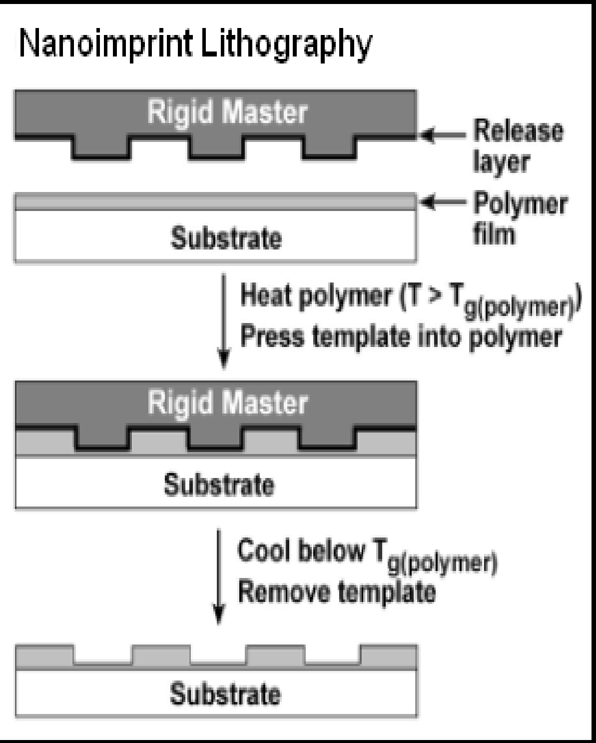
If we let it !



anti-stick, anti-fouling

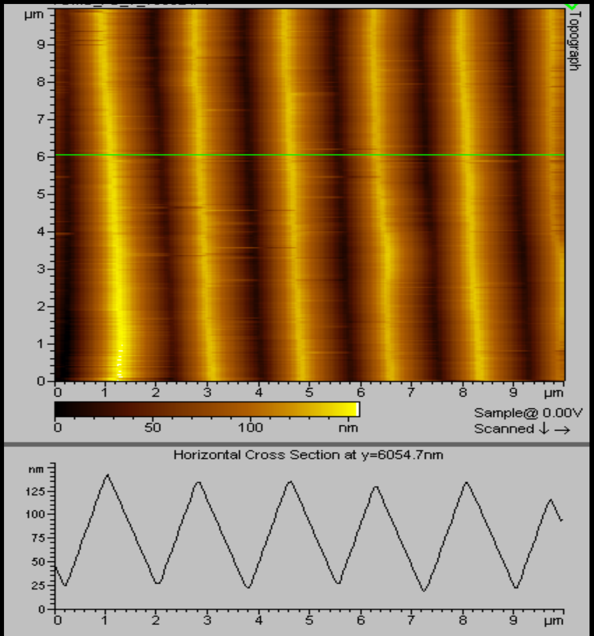
coatings on shark-skin

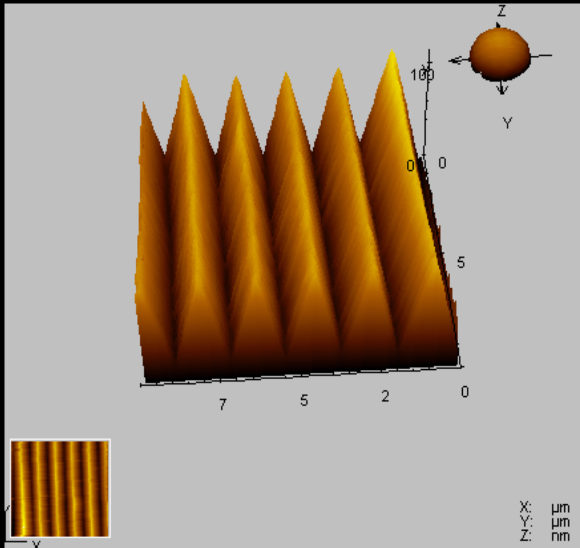
Case Study: Polymeric NANO-structures by Self-organized Splitting of MICRO-structures



PMMA Microstructure Fabrication:
Capillary Flow Lithography plus 30 hours of annealing in vacuum at 160 C

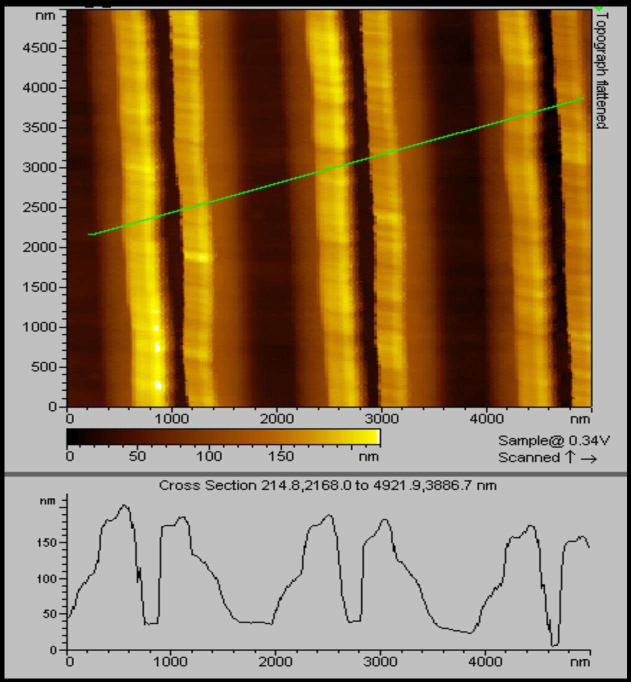
~ 1.5 microns

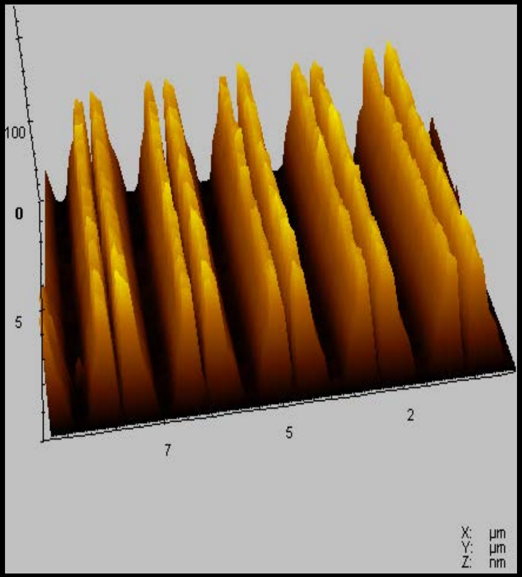


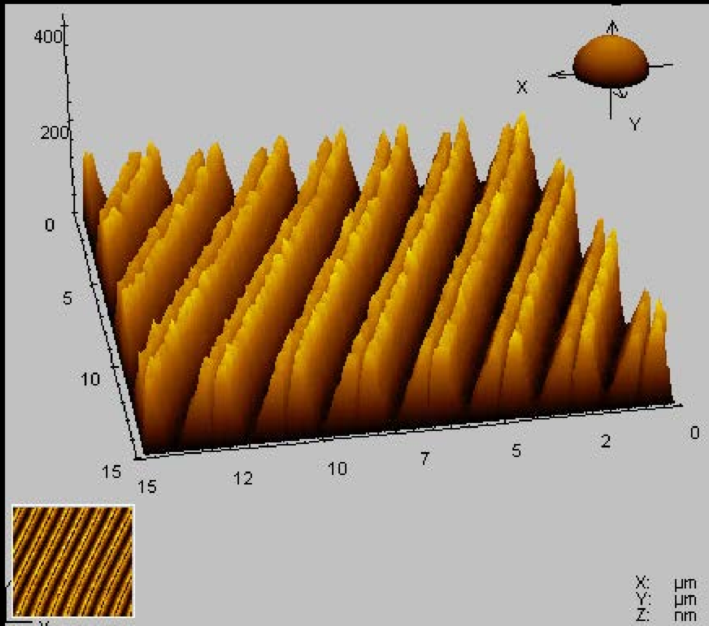


Serendipity Can Really Help, if You Let it!!

Array of Nano-channels: Stress Induced Splitting of Microstructures







Large Area (1 cm) arrays of Nano-channels, ~ 100 nm wide

Some Random Thoughts on the Road to Obvious!

- ✓ Education does NOT equal C(o)M(u)E(x)G(r)D(e).
- ✓ Education is not the CONTENT but the CAPACITY to learn and apply..
- ✓ Peer pressure !!
- ✓ Question and ponder!
- ✓ About INTERVIEWS ☺
- ✓ Running into a wall syndrome…(lateral think)...

General New Directions in 2015

- **Emphasis on Translational Sciences,Technology and Innovation *around Societal Priorities….***
- **Connecting R&D and Innovation with Higher Education, Line Ministries and Industry….**
- **Technologies that keep PEOPLE at the Center…**

Some Cheers 2015 ☺

- **Budget for scientific research increased**
- **India now No. 1 for offshore R&D investments**
- **ASTROSAT-India's first space astronomy mission**
- **India attains 6th position globally in science publications; 3rd position in Nanotechnology and Materials Science**

New Programs Joining Education, Research, Industry and Innovation Spaces

- **Future Ready: National supercomputing Mission (with DeitY) Rs. 4500 Crores/7 years**
- **Meeting National Technological Priorities: IMPRINT (with MHRD). Rs. 1000 Crores/year**
- **Translation: Five Technology Research Centers for indigenous tech in biomedical device, nanotech, energy, water, waste.**
- **400+ new technology startups**
- **Innovation: Technology Research Parks (with MHRD)**

New DST Programs on:

- **Making it:** Advanced Manufacturing
- **Environment:** Waste Management (plastic, e-waste, hospital..)
- **Empowering:** Point of Use Biomedical devices
- **Digging Deeper:** Science & Technology of Yoga and Meditation (SATYAM)
- **Securing climatic and Energy Security:** Clean Energy, Energy Storage and Smart Grids
- **Moving away from Incremental:** High Risk, High Gain
- **Industry Connect:** Ucchatar Aavishkar Yogana (with MHRD)

Trailer 2016

- **Inclusive, frugal and Relevant Innovation:**

Promoting Grass-roots Innovation Ecosystem in Rural Areas, Schools, I. T. I.s and Polytechnics

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“Minds at the margins of economy are not marginal minds”

“Children are not mere sinks of our sermons but can be generator of ideas and innovations”

Translational Research?

Lost in Translation Syndrome !?

To boldly go where no man has gone before.

Korean Translation:

대담하게 아무 남자도 어디에 전에 가지 않은 것은지 가기 위하여

Re-translation:

Makes bold and also anyone man not going a before in where in order to go.

Acknowledgements

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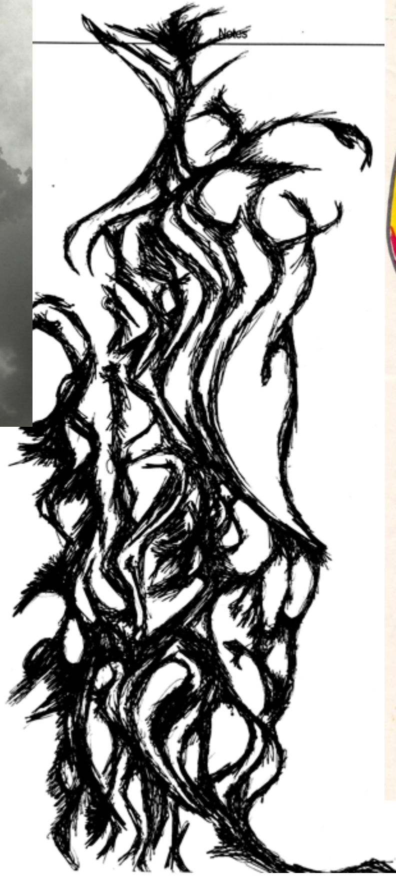
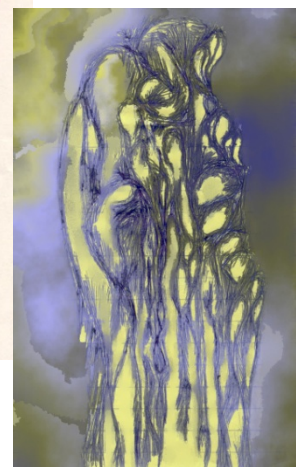
Animangsu Ghatak (IITK)

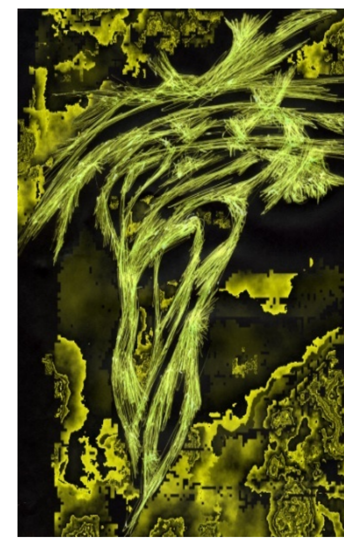
Rajesh Khanna (IITD)

Kajari Kargupta (Jadavpur)

Dif-tor heh smusma







“Truth is stranger than fiction, because Fiction is obliged to ADHERE to possibilities; Truth isn’t”---Mark Twain

"…run up and down a tree in any way, even with the head downwards."- Aristotle 4th century B.C. *Historia Animalium.*

Search for a

reusable,

non-contaminating,

high strength,

self-cleaning,

soft dry adhesive,,,,,,,!!!

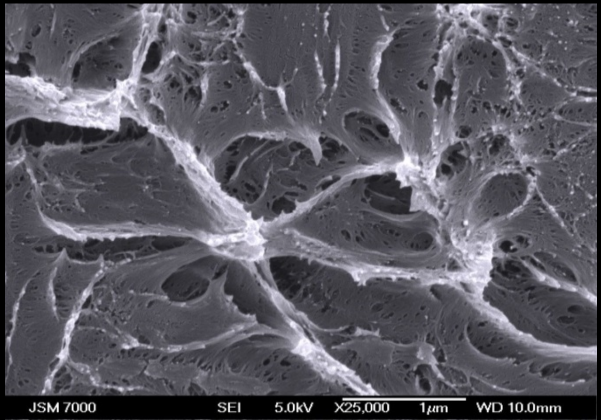
(that also works in water)!!!!

Natural Adhesives

Case Study: Making Re-usable Pressure Sensitive Adhesives

1. Elastic surfaces (more rigid cross-linked PDMS):
Reusable, non-contaminating, but little strength because low contact area and no dissipation

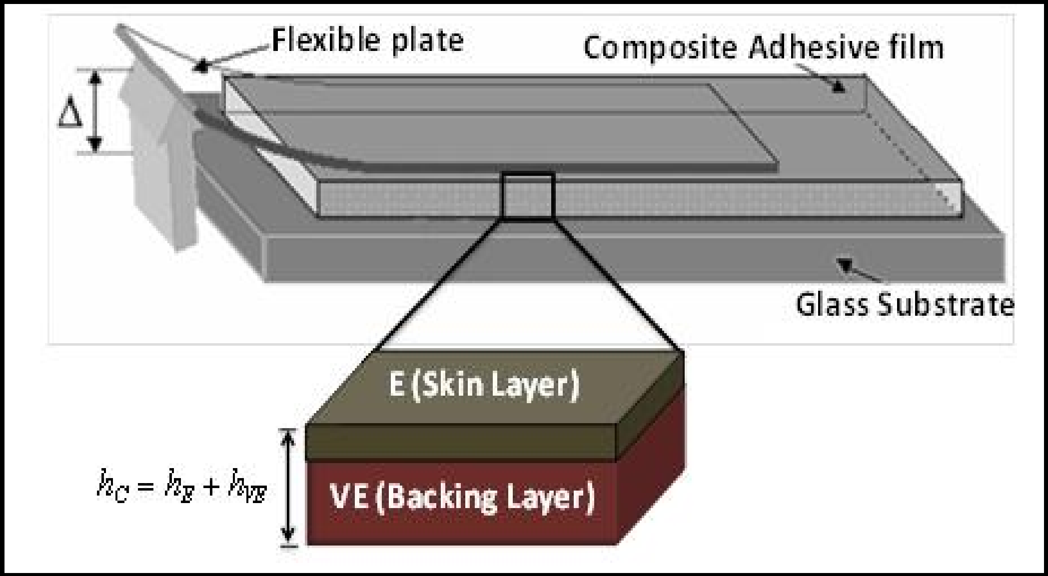
2. Viscous-plastic-elastic & soft (real adhesives):
Good contact, Higher adhesive strength (dissipation). But cohesive failure; contaminating/contaminated and thus not reusable



Visco-plastic dissipation when peeling

Anatomy of a Green (Reusable) Adhesive:

Multiple Function (strength & reusability) Composite Layer

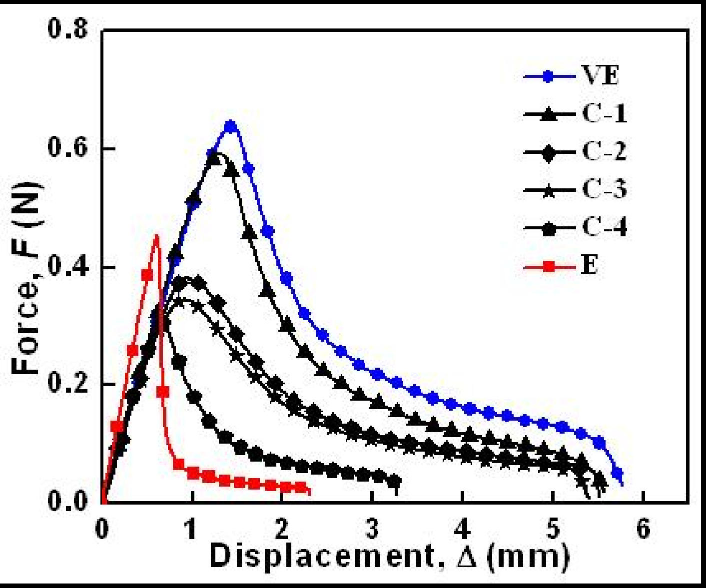


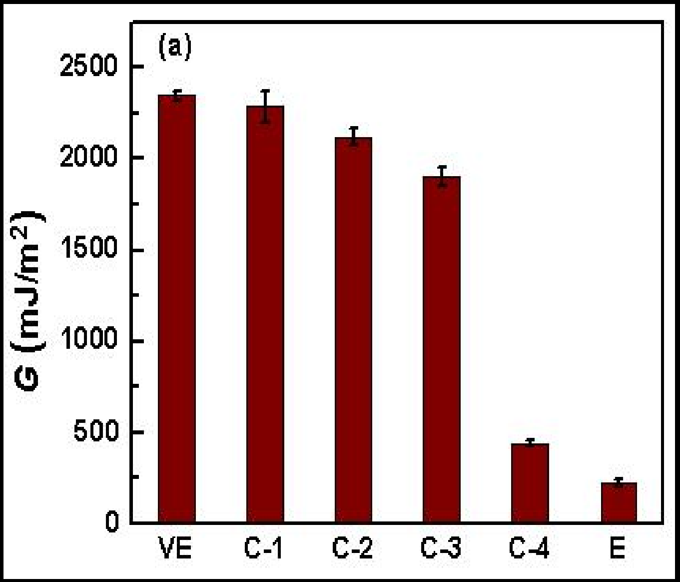
✓ **For skin layer < 100 nm, little change in elastic compliance; good contact on pressing; Detachment Strength is controlled by dissipation in viscous-elastic backing layer.**

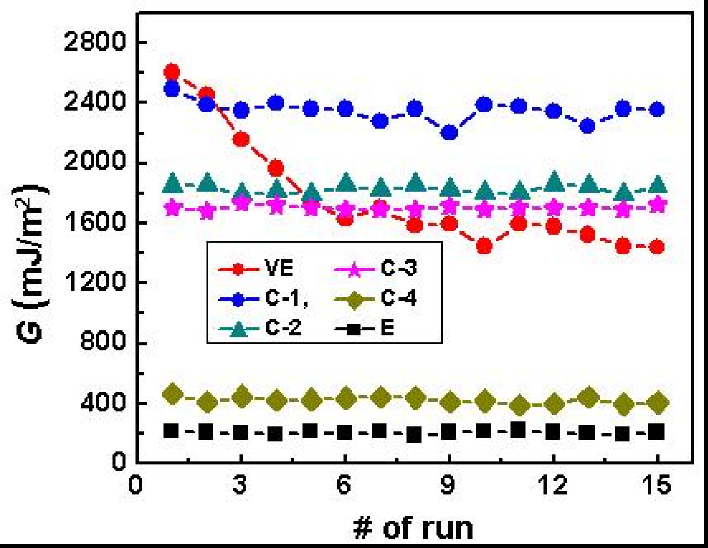
✓ **Non-fouling, reusability by thin (< 1 micron) elastic skin..**

Langmuir 2012; *US patent applied*

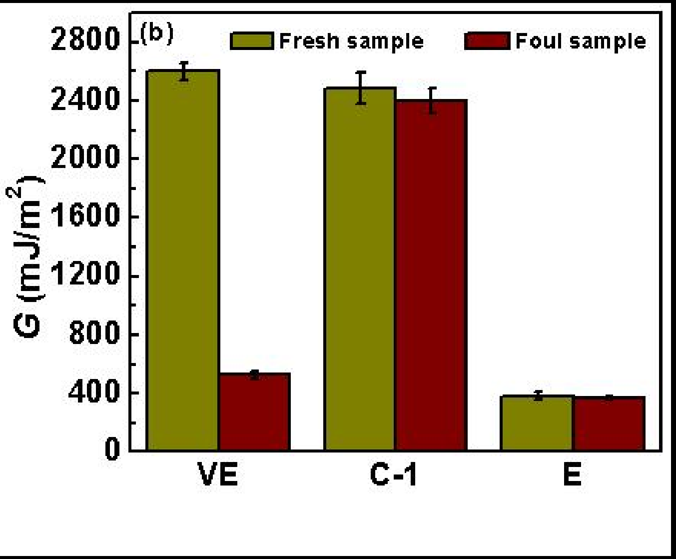
Tunable Adhesion by Skin Thickness



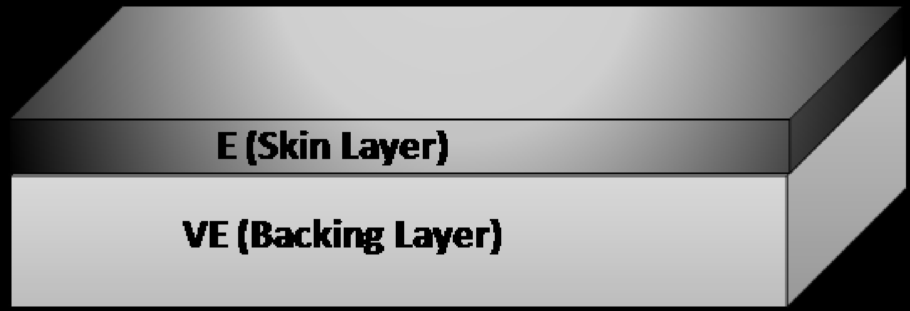




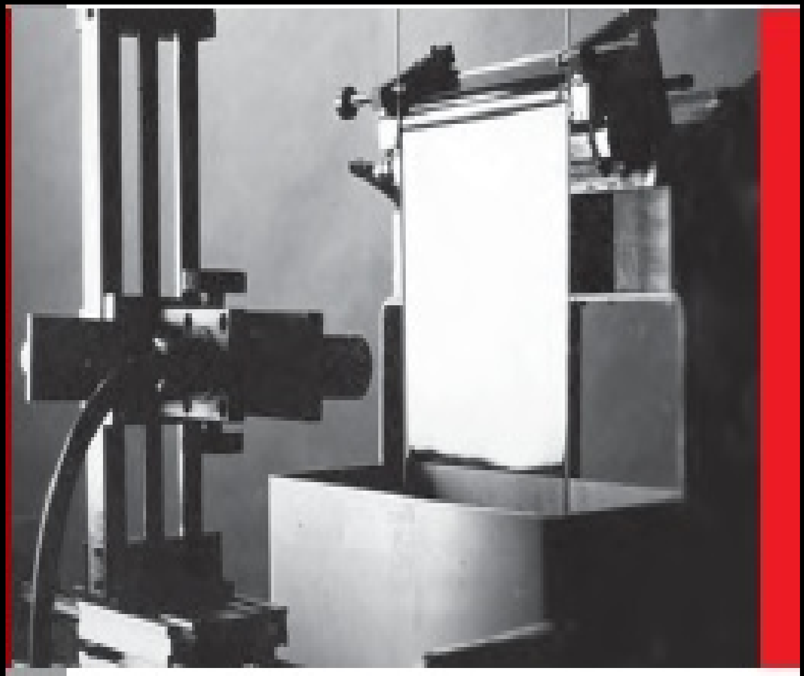
Reusability

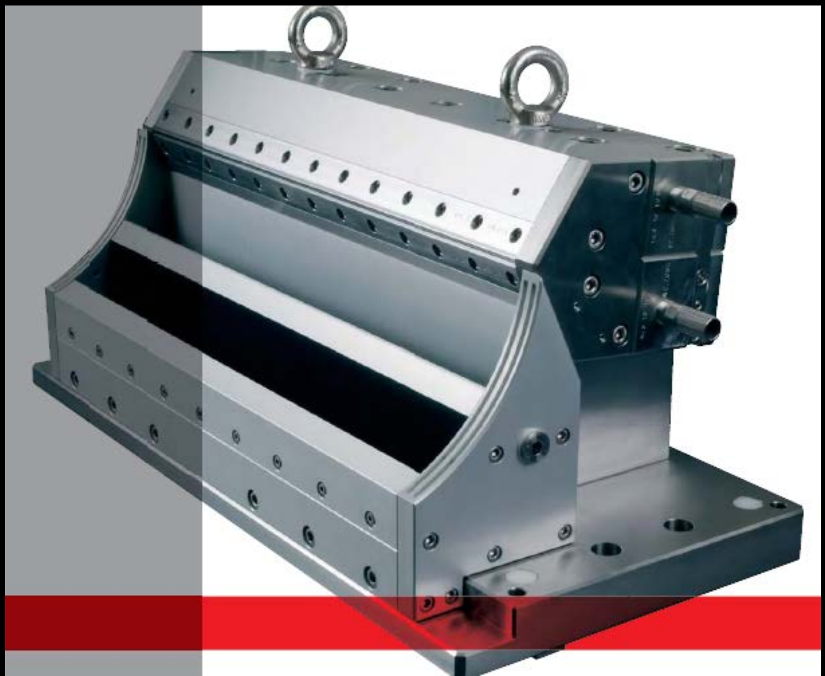


Skin Thickness: C1 (< 1% skin thickness; C2 ~ 5%; C3 ~ 8%; C4 ~ 25%)



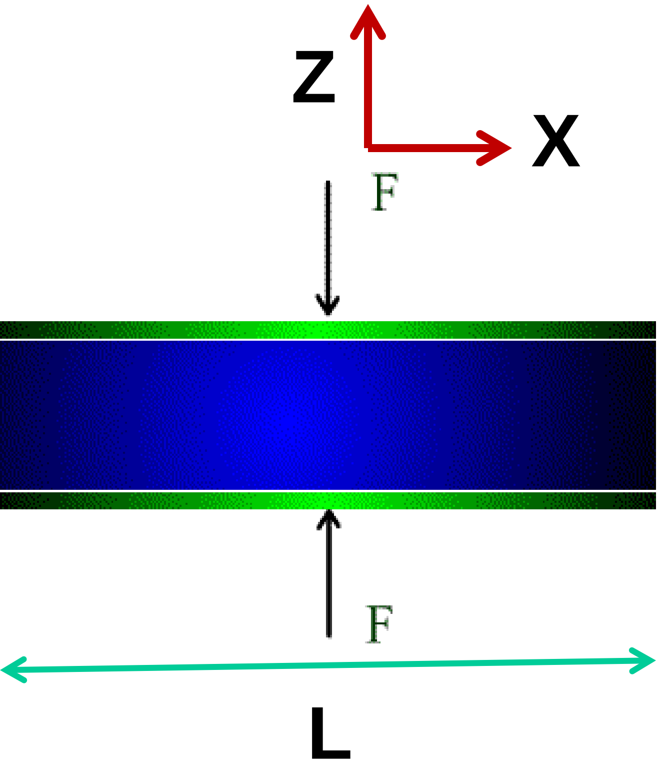
Roll to-roll manufacturing friendly green adhesive





Failure of Classical Mechanics in Thin Film Wetting !

Adhesion of surfaces/particles in a liquid



(N-S eqn) $\mu\ \partial^2 U/\partial Z^2 = \partial P/\partial X$

$\Rightarrow$ $U \sim (H^2/\mu)\ (P/L)$

(continuity) $\partial W/\partial Z + \partial U/\partial X = 0$

$\Rightarrow$ $W \sim (H^3/\mu)\ (P/L^2) = dH/dt$

as H $\rightarrow 0$, V $\rightarrow 0$

Infinite time for adhesion!

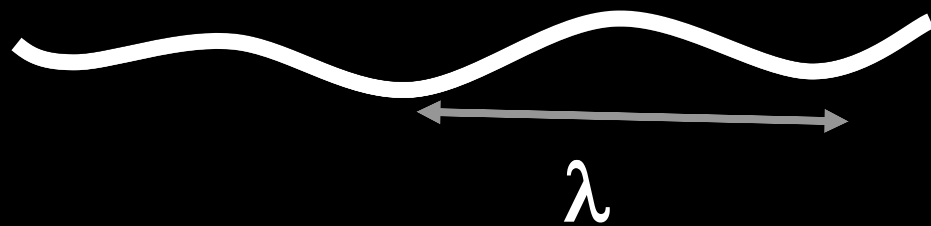
But, for H < 50 nm, van der Waals force rescues!:

P (van der Waals) ~ $1/H^3$ and thus, V ~ constant; finite lifetime

An Anthropomorphic Projection?

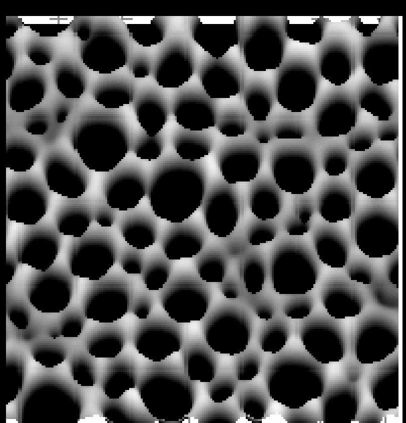
Spinodal Dewetting in Thin Liquid Films: A Surface Force Measurement Apparatus

$$3\mu\,(\partial H/\partial T) + \nabla.[\gamma\, H^3\, \nabla\nabla^2 H] - \nabla.[H^3\, \nabla\Phi] = 0$$



Wavelength of Instability (**λ**):

$$\boldsymbol{\lambda}^2 \sim N^{-1} \sim \gamma\, /\, [\partial^2 G/\partial H^2] \sim \gamma\, \boldsymbol{/}\, \phi$$



$\lambda \sim H^2$ (van der Waals force)

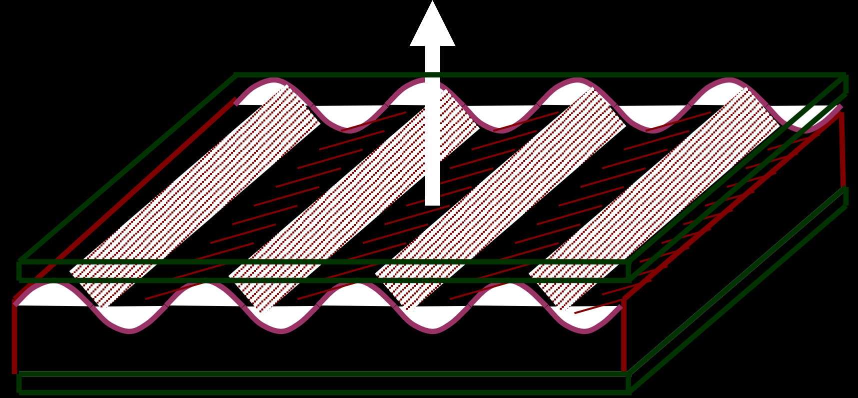
$\lambda \sim H^{1.5}$ (electrostatic force)

PRL 1998, 2000, 2002

Soft Adhesion Engenders Surface Instability and Micro-texture

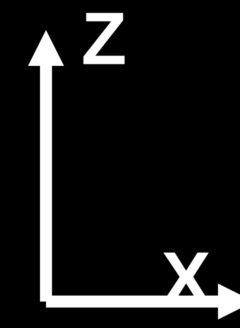
Contact Instability

PRL 2004, 2006; Adv Mat 2006



L = wavelength

A = amplitude



Energy / area ~ Elastic Energy + Adhesive

$$\text{Energy} = \mu H \left[(\partial V/\partial X)^2 + (\partial U/\partial Z)^2 \right] - A^2 \Phi_H$$

Scalings: $X \sim L$, $Z \sim H$, $V \sim A$, and $U \sim AL/H$

$$\text{Energy} = \mu H A^2 (L^2 / H^4 + 1/L^2) - A^2 \Phi_H$$

Minimum elastic energy: *L ~ 3H*

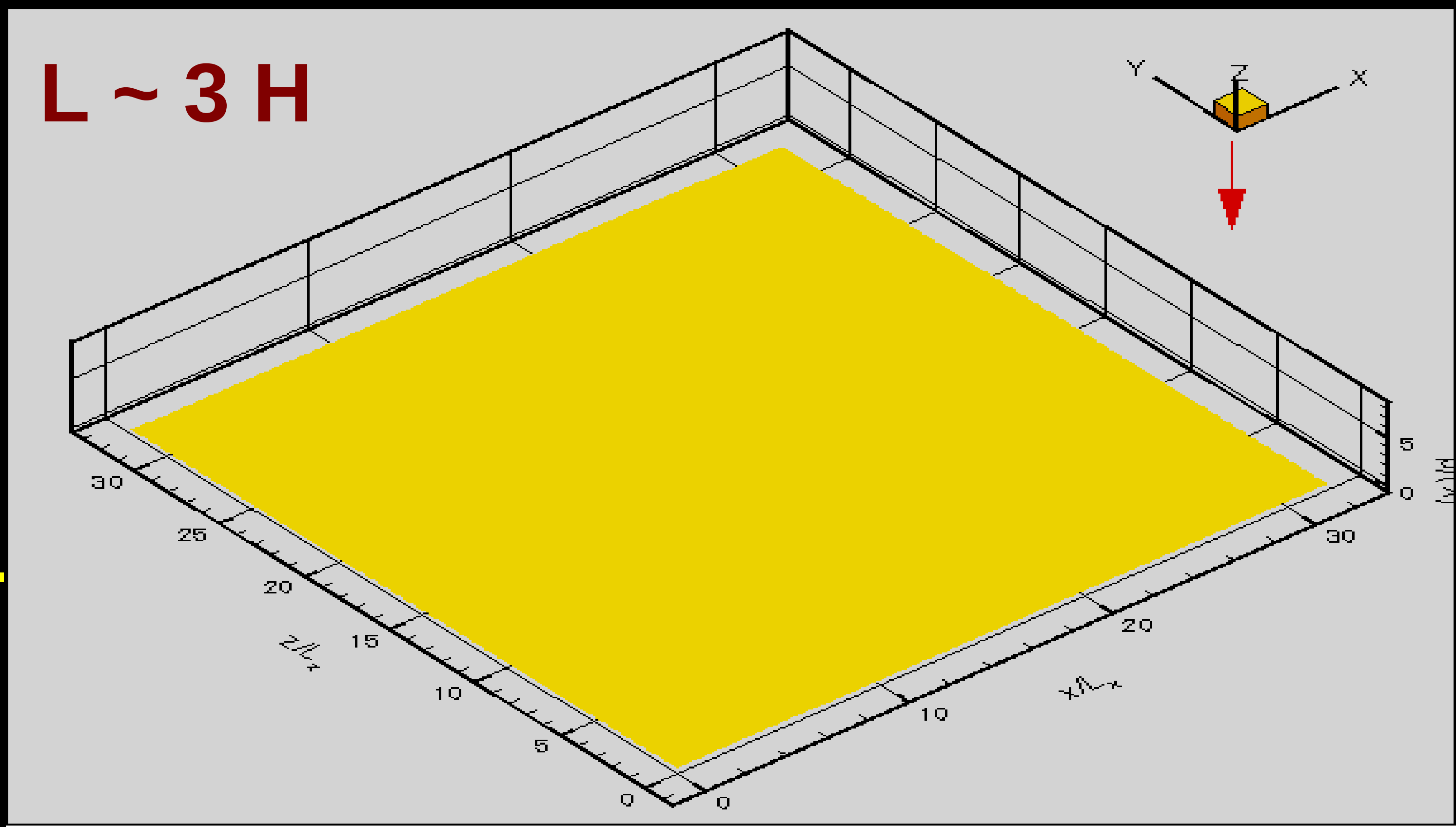
Independent of all properties !!

PRL 2000, 2001

Patterns during Approach and Retraction of a Contactor:

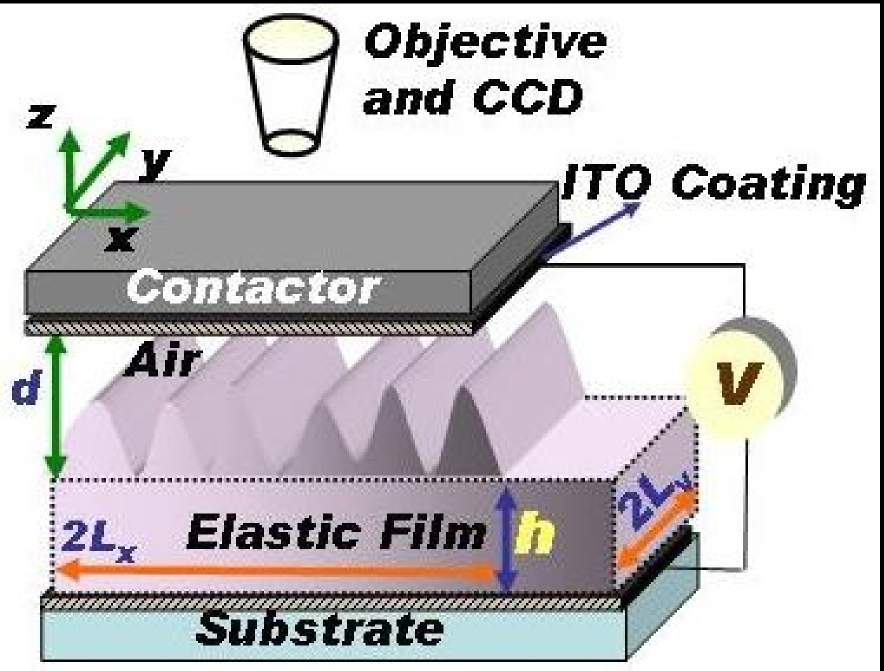
Surface profiles by Minimization of Energy

$$\boldsymbol{\Pi} = \int_{\boldsymbol{V}} W(\boldsymbol{\varepsilon})\,dV + \int_{S} \left(\gamma \sqrt{1 + \left(u_{2,1}\right)^{2}} - U(\boldsymbol{u}.\boldsymbol{n}) \right) dS$$

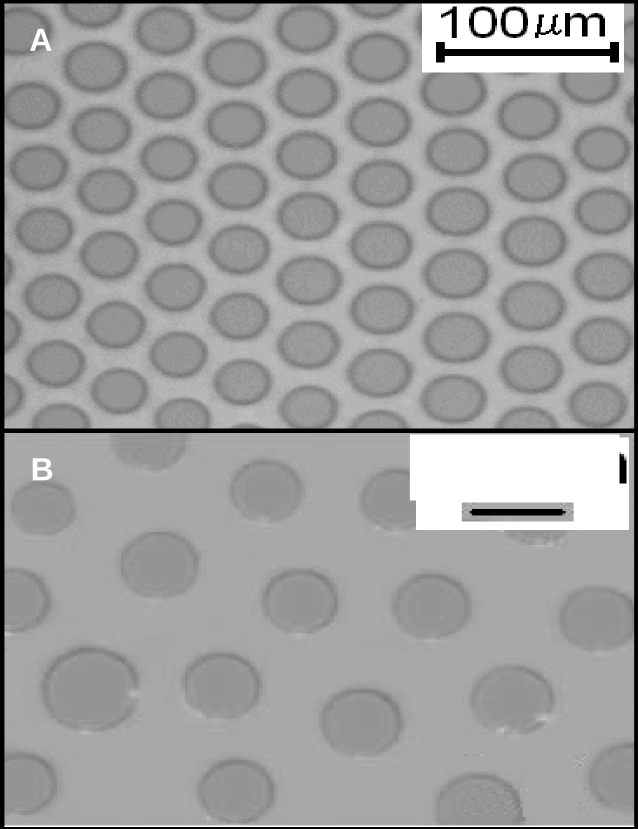


Shenoy, Sharma, et al.
PRL 2001
2004

Initiating Instability by Electric Field (rather than VdW)



1.5 % visco-elastic liquid;
H = 7 µm; V = 30 V



3 % visco-elastic solid;
H = 70 µm; V = 30 V

Length scale control by Rheology

Visco-elastic LIQUID

(Surface energy dominated)

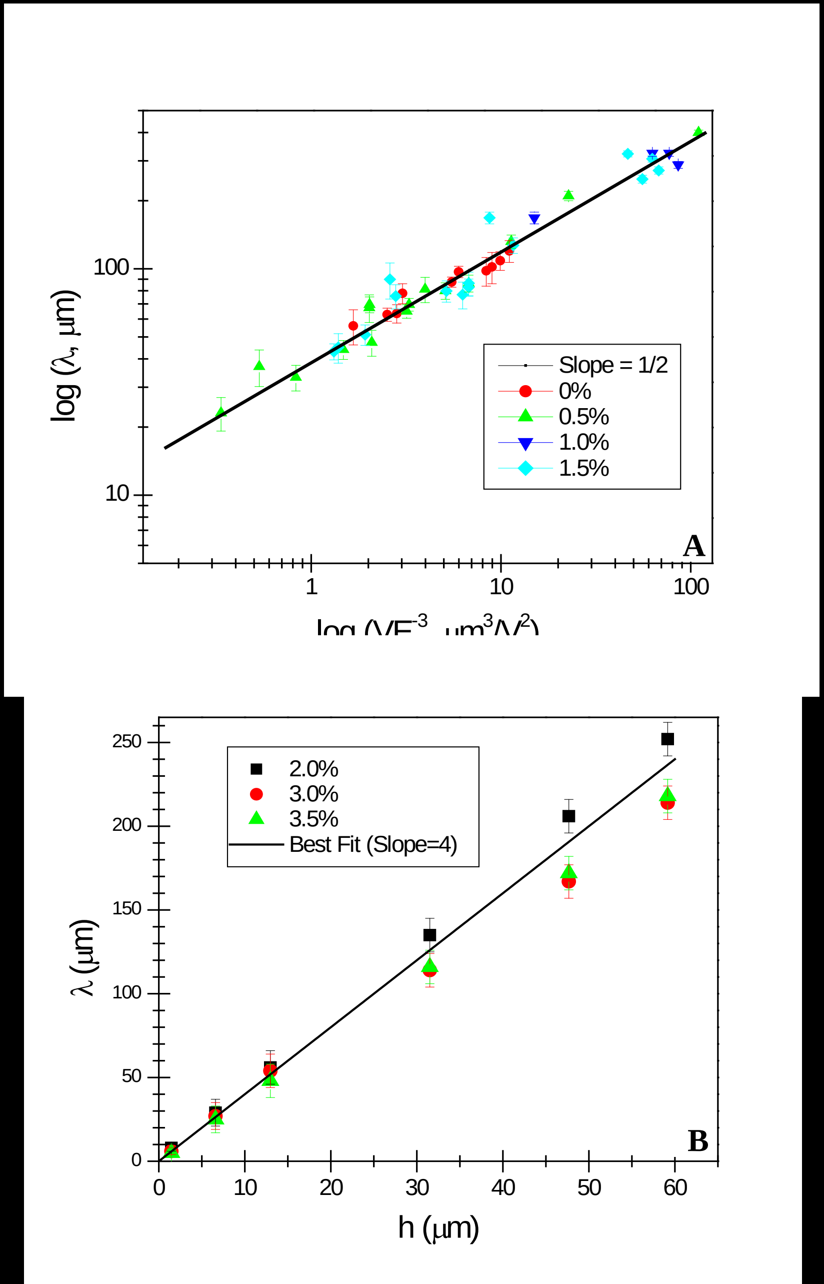
Cross-linker < 1.8%

$$\lambda^2 \sim \gamma / [\partial^2 G/\partial H^2] \sim \gamma / \phi$$

Visco-elastic SOLID

(elastic energy dominated)

$$\lambda \sim 3\text{-}4\ H$$

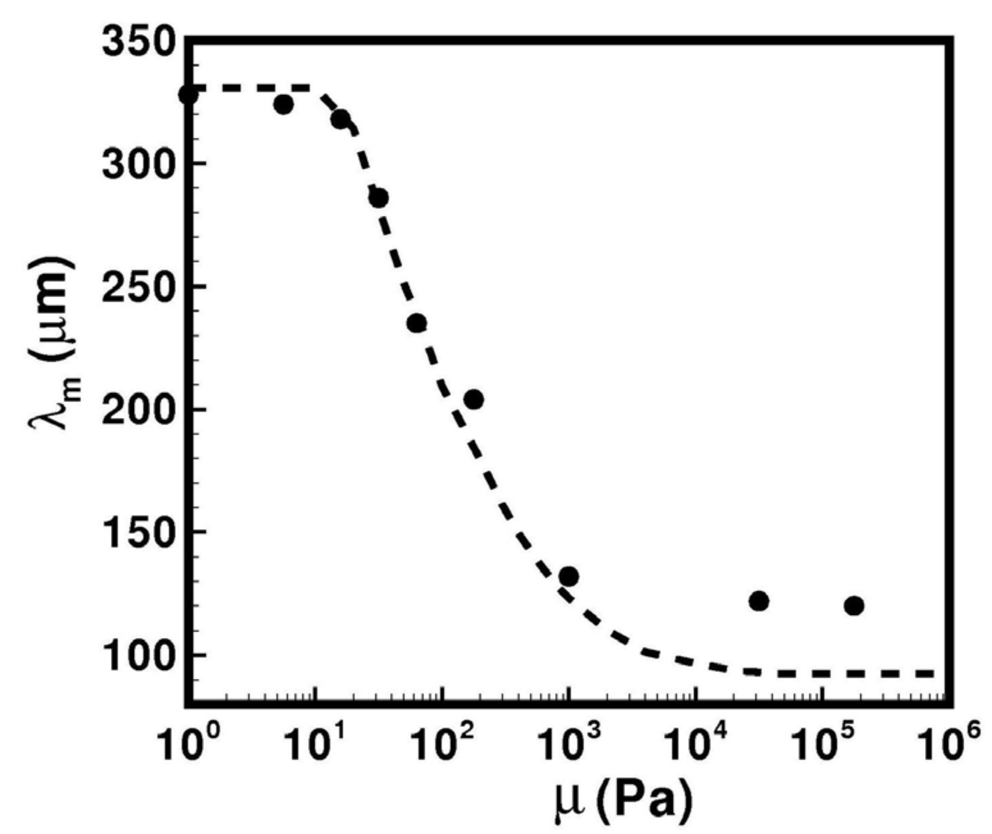


PRL (09); Adv Mat (07)

Transition from Liquid-like to Solid-like Modes: From long to short waves

$$(\gamma/\mu h) \sim 1$$

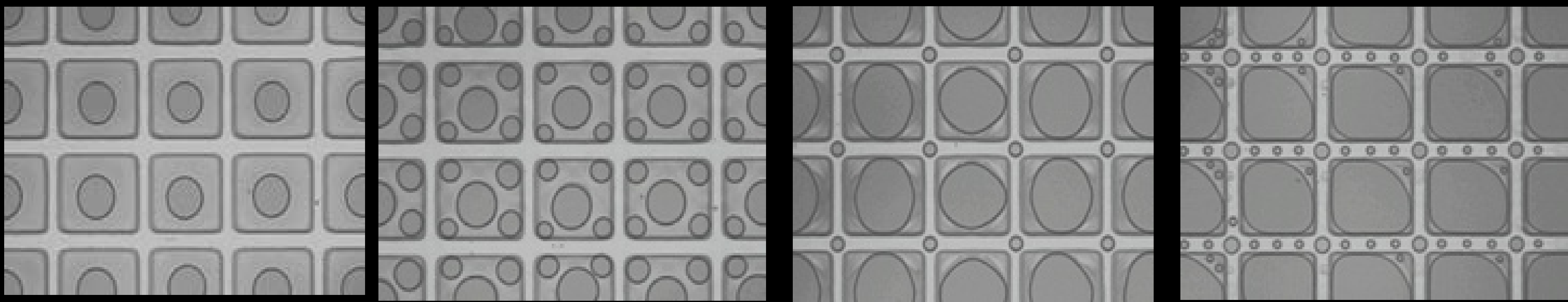
- μ is Elastic shear modulus
- γ is Surface energy



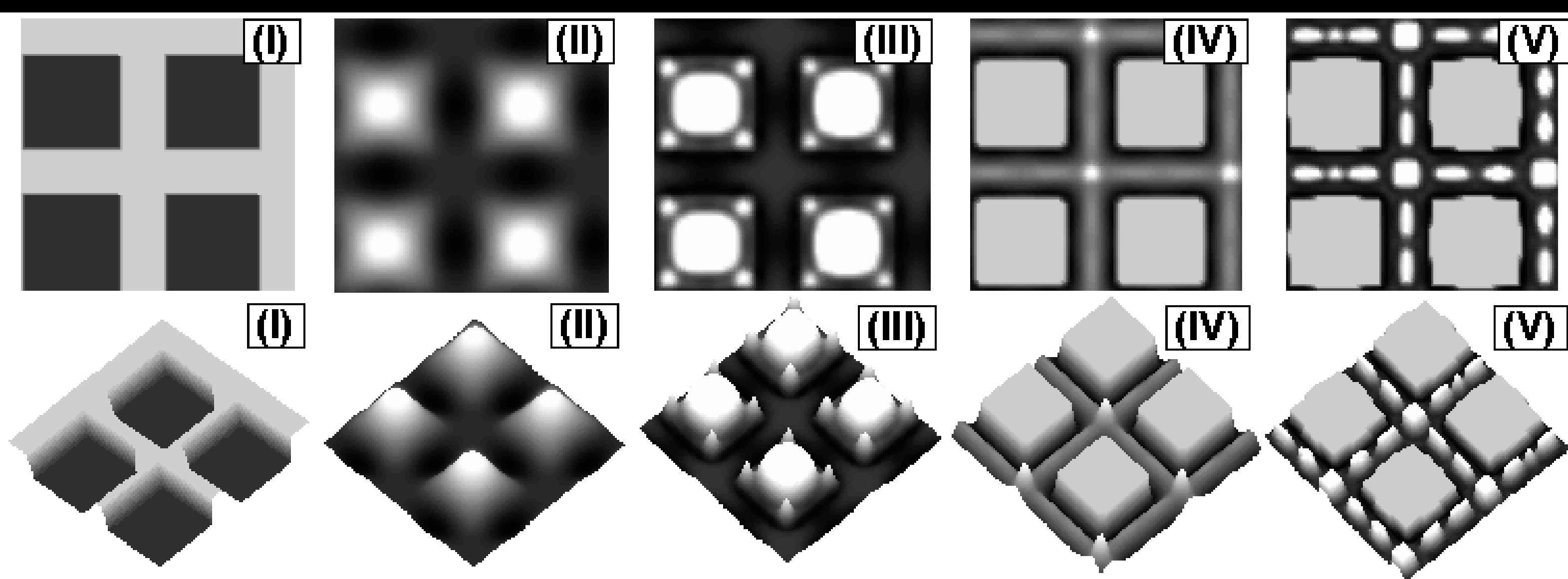
h=31.5 μm, *d* = 50 μm; V = 30 V

PRL 2009

Hierarchical Structures by Rheology Control & Spatio-temporal Variation of e-Field: Pixel Electrode

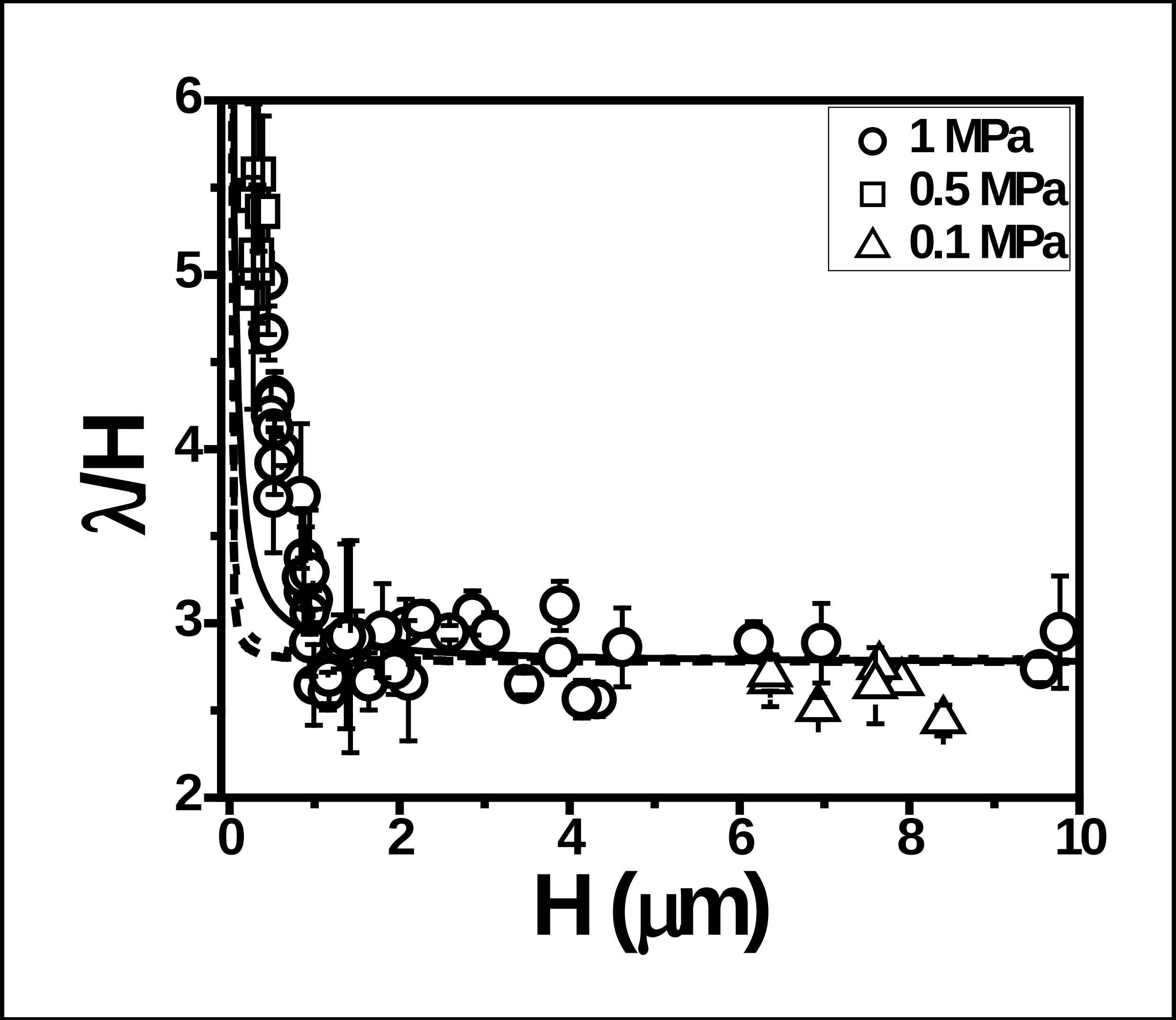


30 V- 50 sec | 50 V-2 min | 100 V-2 min | 130 V-9 min



***Adv Func Mat* 2010**

Pattern Length Scale: Role of Surface Energy



PRL 2006