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Electric field induced instability in ultra-thin films

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Patterns at nano/micro-scale

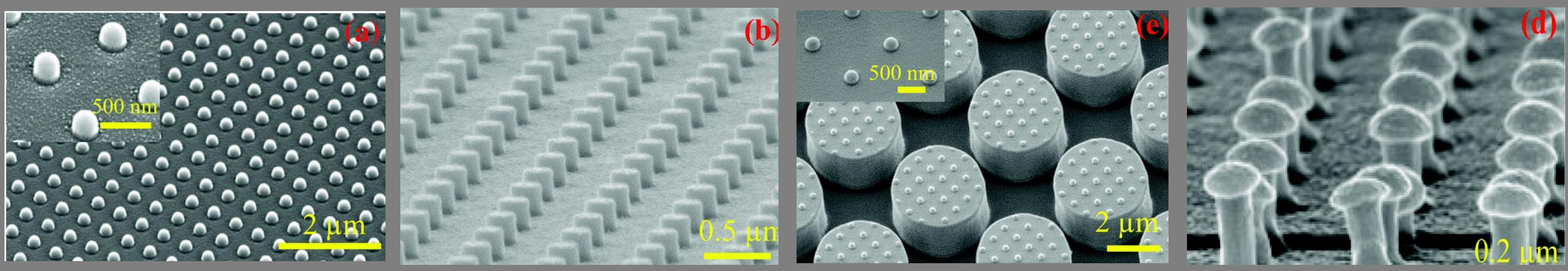
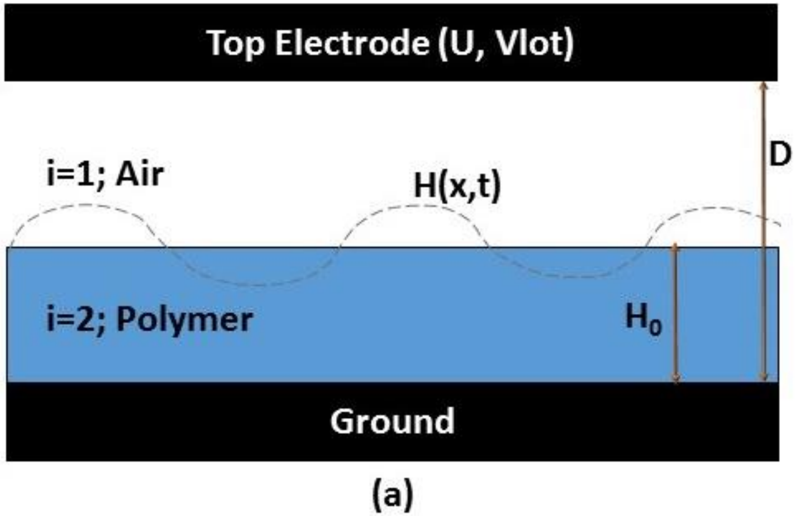
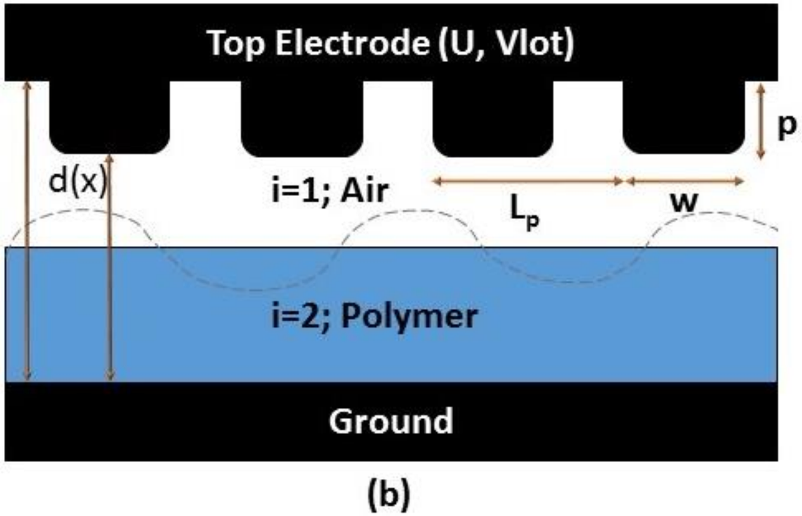


Image source: RSC, Nanotoday : DOI: 10.1039/C4NR04069D

Microfluidic devices, semi-conductor devices, emulsions and coatings are just to name a few applications[6]

Schematic





Top electrode – Flat plate
Homogeneous field

Top electrode – Patterned mask
Heterogeneous field

- Period limit (L_p), protrude width (w), protrude height (p), electrode spacing(D), lateral electrode distance (d), and initial film thickness (H_0) are shown in the schematic.

- Interface is perturbed either because of its own thermal fluctuations or externally. [8,9,10]

Assumptions and Equations

- **2D** model is developed
- System is **isothermal**
- The polymer and air are **Newtonian** fluids
- Polymer fluid is considered to be **perfect dielectric**
- All material properties are **constant**.
- The incompressible **Navier–Stokes** equations and continuity are introduced to describe the flow.
- Inertial terms are neglected.

$$\rho_i \left[\frac{\partial \overrightarrow{u_i}}{\partial t} + (\overrightarrow{u_i} \cdot \nabla) \overrightarrow{u_i} \right] = -\nabla p_i + \nabla \cdot \left[\mu_i (\nabla \overrightarrow{u_i} + (\nabla \overrightarrow{u_i})^T) \right] + \overrightarrow{f_i}$$

$$\nabla \cdot (\overrightarrow{u_i}) = 0$$

Assumptions and Equations

- Electrical force is included as a **body force** term.
- Force acting on the interphase is given by,

$$F = -\frac{1}{2}\epsilon_o \nabla\epsilon E.E$$

- This force can in-turn be given in a pressure force form using stress boundary condition as[1,7,8],

$$P_{el} = -0.5\ \epsilon_o\ \epsilon\ (\epsilon-1)\ E^2$$

- This pressure is applied as a body force term in computational model using **delta function**.
- Electrostatics module solves the **Laplace** equation,

$$\nabla\epsilon\nabla V = 0$$

Flat electrode system

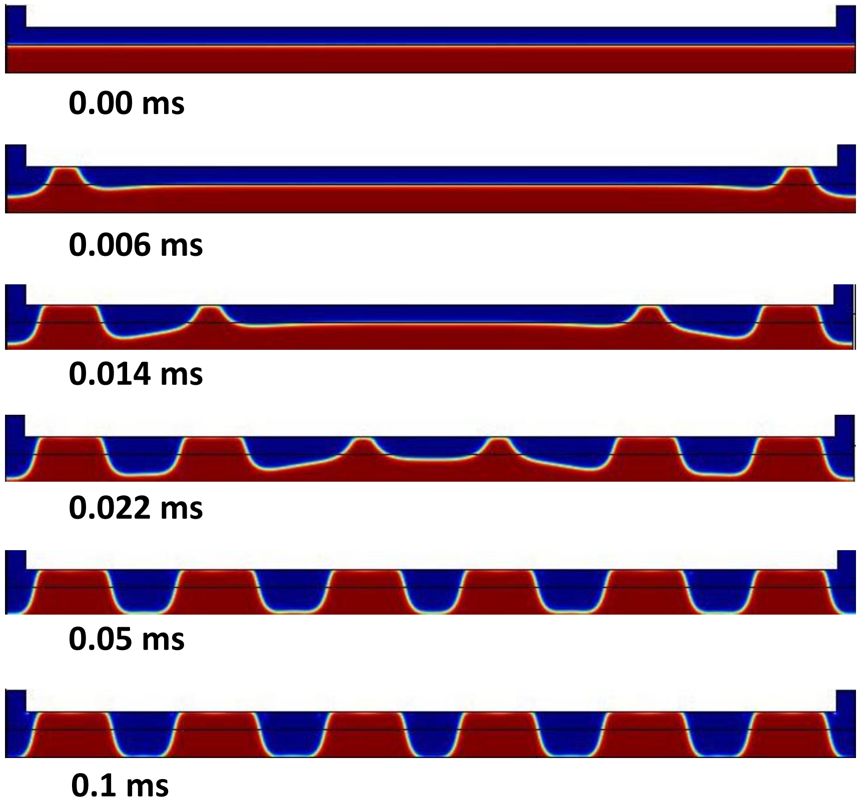
Model Description

$$\lambda_c = 2\pi \sqrt{\frac{2\sigma U}{\varepsilon_0 \varepsilon_p (\varepsilon_p - 1)}} E_p^{-3/2} \qquad E_p = \frac{U}{\varepsilon_p d - (\varepsilon_p - 1) h}$$

Parameters

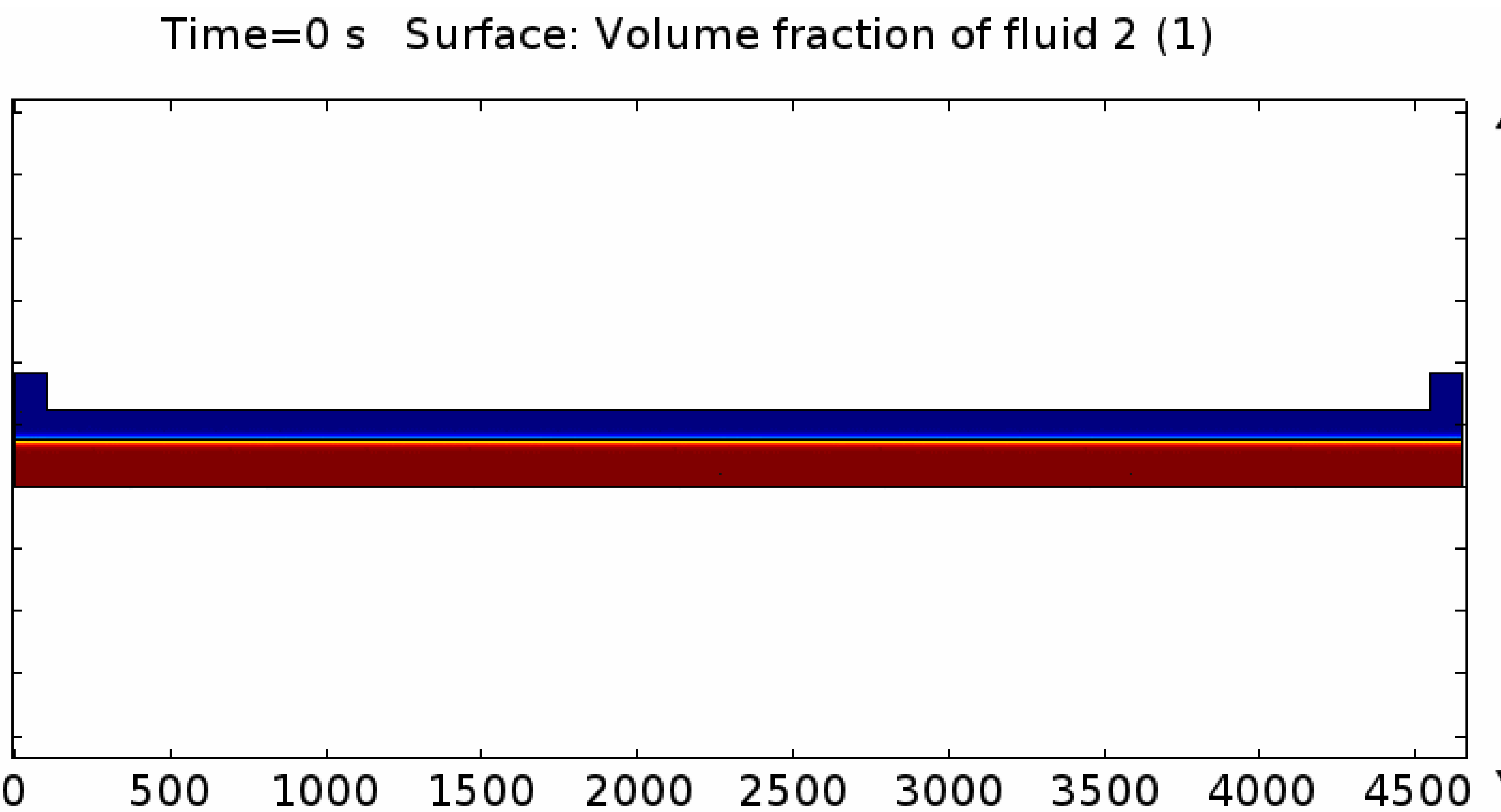
U =30 Volt
σ = 0.03 N/m
ε_p =10
d= 250 nm
h= 150 nm

Validation

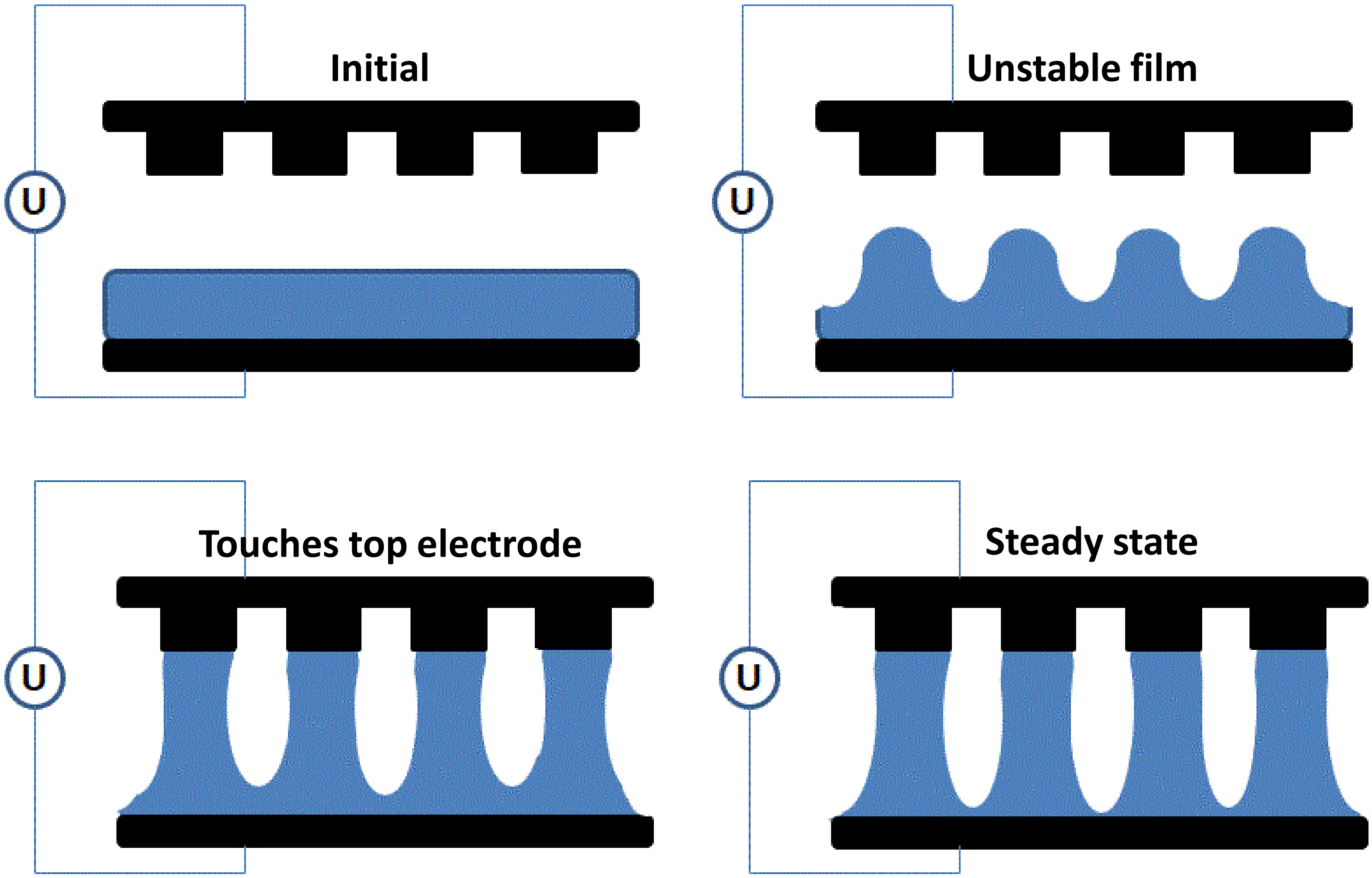


Fastest growing wavelength=780 nm

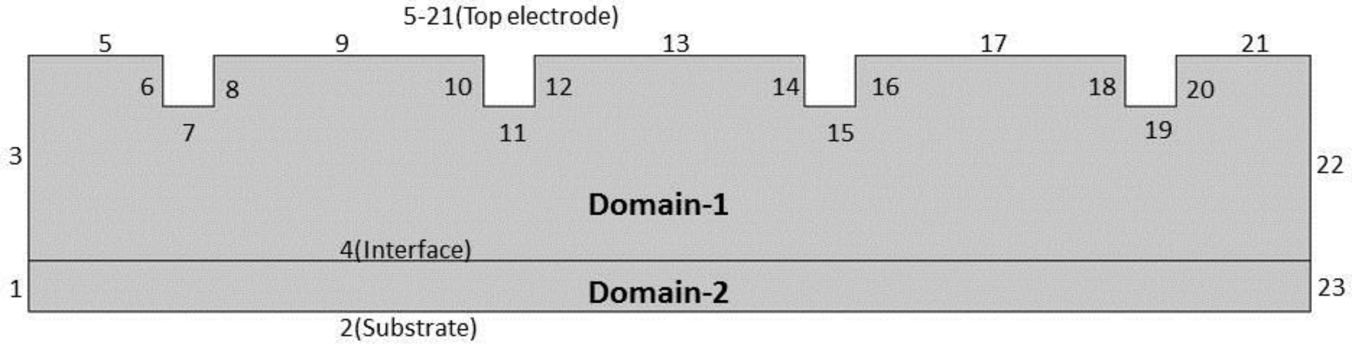
Fastest growing wavelength in linear stability analysis[3] =740 nm

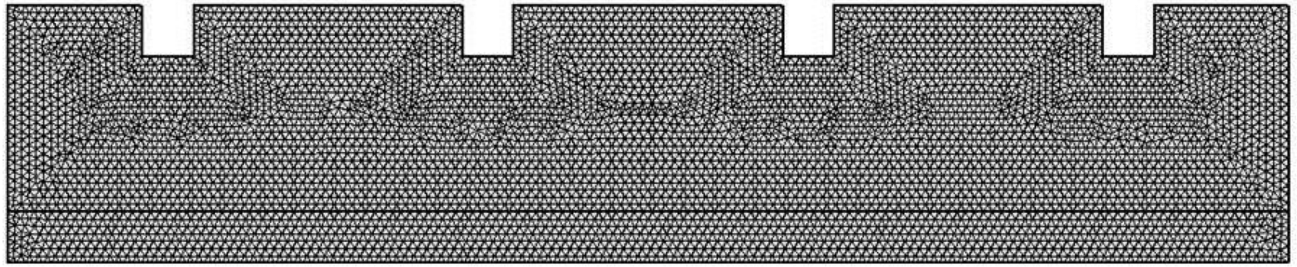

Time=0 s Surface: Volume fraction of fluid 2 (1)
0
500
1000
1500
2000
2500
3000
3500
4000
4500

Patterned electrode



Computational model





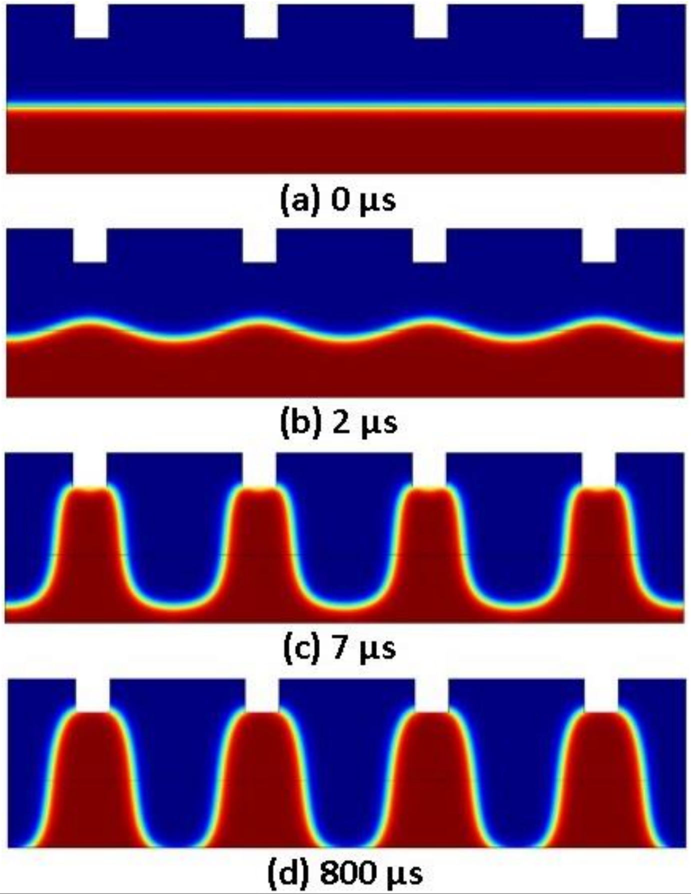
Domain
1 – Air
2 – Polymer liquid
Boundary
5-21 – Top Electrode
(Wall and Potential U)
2 – Ground
(Wall and Potential 0)
4 – Interface
1,3 & 22,23 – Periodic

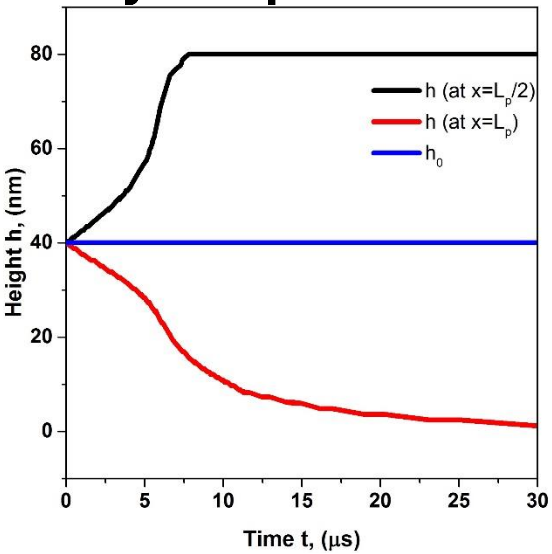
Physics controlled meshing has been done over the system domain

A two dimensional computational model has been developed using COMSOL Multiphysics 5.0

Pillar formation, Exact replication

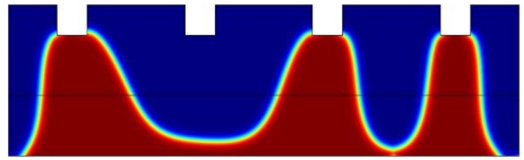
- A polymer fluid is coated on ground electrode, bounded by air.
- Heterogeneous electric field destabilizes the interface.
- Surface tension opposes while electrical pressure difference drives the flow.
- Liquid flows from falling crests towards rising peaks.
- Polymer pillars attain pseudo steady state.



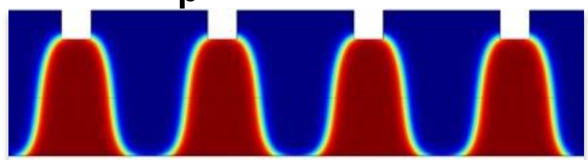


70 V electrical potential is applied through an electrode assembly having 20 nm × 20 nm square protrusions with periodicity of 100 nm and100 nm electrode spacing

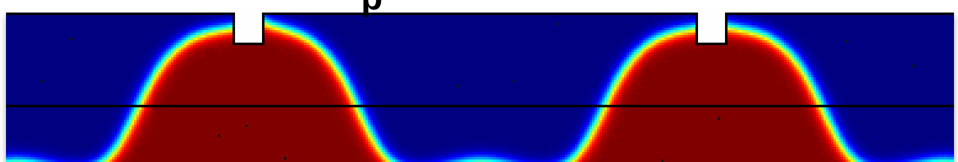
Effect of period limit



L_p = 85 nm

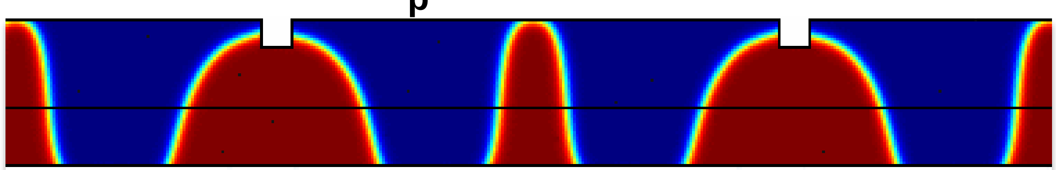


L_p = 100 nm



L_p = 300 nm

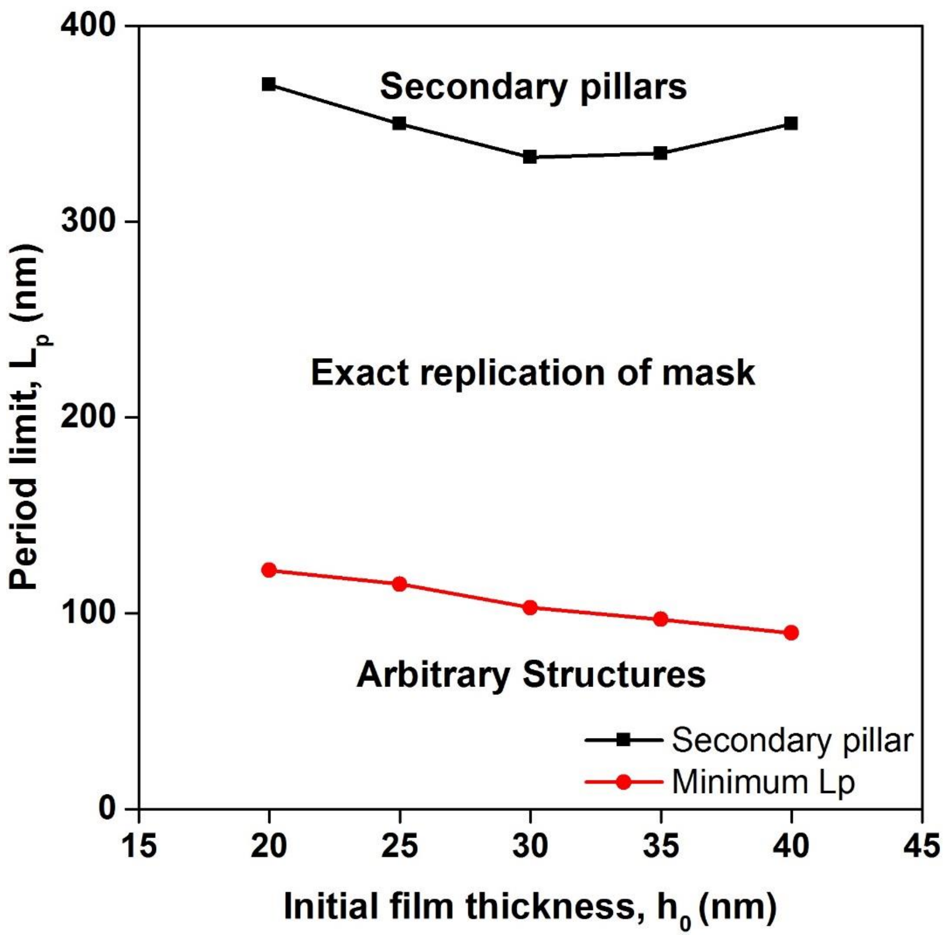
L_p = 340 nm



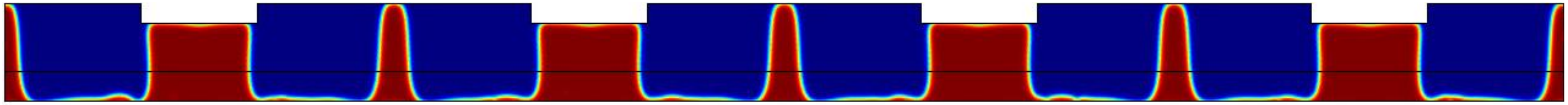
L_p = 350 nm

Limitations of patterned electrode

- Verma et al.[1] suggested later quantified by Li et al.[4], a minimum Period limit required for exact replication of mask
- Upper bound of the same has computationally reported here.
- An unusual trends in the upper limit can be explained when dynamics is observed carefully.



Effect of electrode width



w=80 nm, p=20 nm, L_p=400 nm

w=150 nm, p=20 nm, L_p=400 nm

w=180 nm, p=20 nm, L_p=400 nm

For all cases

U=100 V, D=100 nm, H_0=30 nm

Final Remarks

- Electric field induced patterning supersedes conventional patterning techniques due to its fast dynamics and low cast.

- A competition between surface tension and electrical forces characterizes a specific wavelength to the system.

- For flat plate, periodicity of structures is equivalent to critical wavelength.

- Linear stability analysis predicts characteristic wavelength (λ_c) for flat plate as

$$\lambda_c = 2\pi \sqrt{\frac{2\sigma U}{\varepsilon_0 \varepsilon_p (\varepsilon_p - 1)}} E_p^{-3/2}$$

Final Remarks

- Corner of top electrode helps in rise of instability because of different local electric field.
- Patterned electrode can reduce characteristic lambda of the system resulting in more densely packed pillars.[5]
- Range of nano/micro structures can be obtained by varying period limit.
- Varying electrode width can control morphologies effectively and novel patterns can be developed.

References

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