Wetting and dewetting of solid films

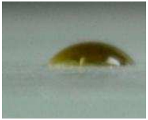
Olivier Pierre-Louis

ILM-Lyon, France.

24th October 2017

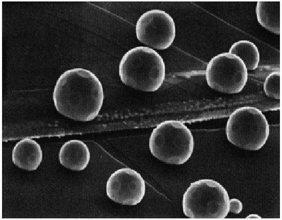
Wetting and dewetting of liquid and solid films

Some examples



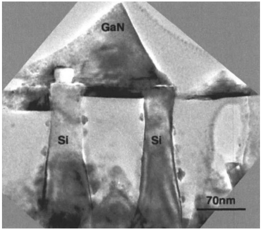
Au/Graphite

J.-J. Métois



GaN on Si nano-pillars

Hersee *et al* J.A.P. 2005



Equilibrium shape, Wulff 1901, Kaishew 1950

Free energy

$$\mathcal{F} = \int_{VS} \mathrm{ds}\, \gamma_{VS}(\theta) + \int_{SA} \mathrm{ds}\, \gamma_{SA}(\theta) + \int_{AV} \mathrm{ds}\, \gamma(\theta)$$

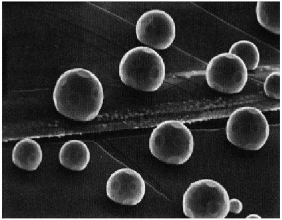
Total number of atoms

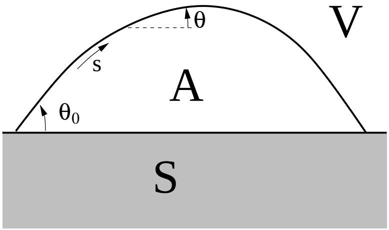
$$\mathcal{N} = \Omega^{-1} \int \int_{\mathcal{D}} \mathrm{d}^2\mathbf{r}$$

Minimal shape: $\delta(\mathcal{F} - \mu\mathcal{N}) = 0$
Equilibrium Equations

$$\begin{aligned} \Delta &= \gamma_{VS} - \gamma_{SA} \\ \text{Stiffness } \tilde{\gamma}(\theta) &= \gamma(\theta) + \gamma''(\theta) \\ \text{Wulff : } \mu &= \Omega\tilde{\gamma}(\theta)\kappa \\ \text{Young : } \Delta &= \gamma(\theta_0)\cos(\theta_0) - \gamma'(\theta_0)\sin(\theta_0) \end{aligned}$$

J.-J. Métois, Au/Graphite





Isotropic

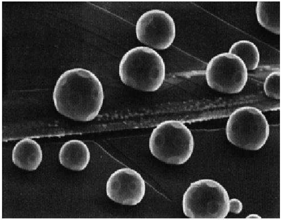
Isotropic solid $\gamma(\theta) = \bar{\gamma}$

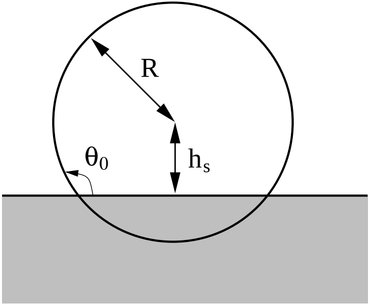
$$\mu = \Omega\bar{\gamma}\kappa \quad \Rightarrow \quad R = \frac{\Omega\bar{\gamma}}{\mu}$$

$$\bar{\gamma}\cos(\theta_0) = \Delta \quad \Rightarrow \quad h_s = -\frac{\Omega\Delta}{\mu}$$

μ fixed from $\mathcal{N} = (\theta_0 - \sin[2\theta_0]/2)R^2/\Omega$

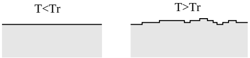
Transition:
Partial wetting $\rightarrow$ complete wetting
when $h_s \rightarrow -R$, i.e. $E_S = \Delta + \bar{\gamma} \rightarrow 0$

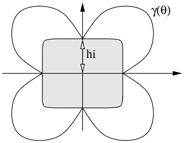




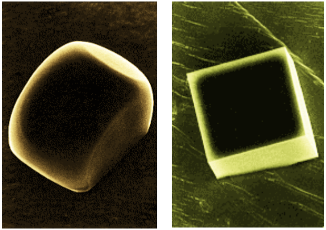
Facets

Roughening temperature T_r

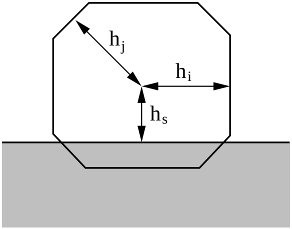




NaCl, Métois et al (620-710^{o}C)



For usual crystals $T_r \sim T_M$



$$h_i = \frac{\Omega\gamma_i}{\mu}$$

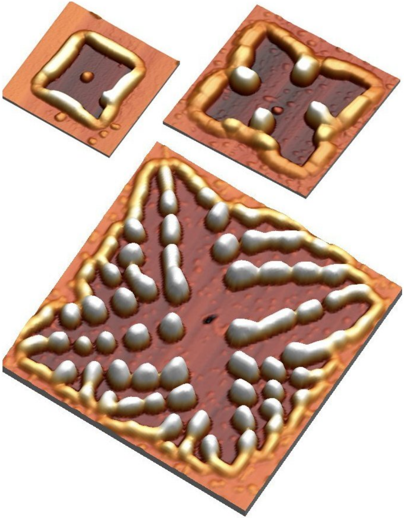
$$h_s = \frac{\Omega\Delta}{\mu}$$

Wetting and dewetting of liquid and solid films

Dewetting experiments: surface diffusion + anisotropy

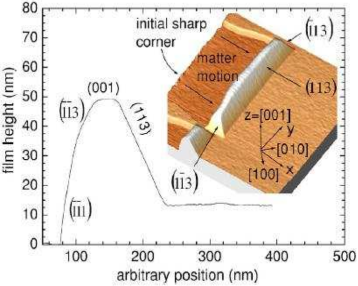
Experiments SOI: Si(100)/a-SiO_2

P. Müller et al Cinam Marseille



SOI (Si/SiO_2), AFM

Dornel Barbe Crecy Lacolle Eymery PRB2006



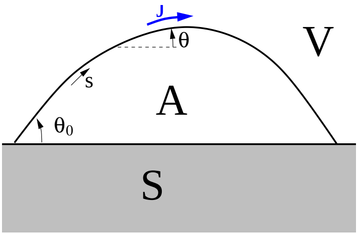
Surface Diffusion Mullins' Model

Local chemical potential $\mu = \Omega\tilde{\gamma}\kappa$.
Mullins model:

$$\begin{aligned} j &= -\frac{Dc}{k_B T}\partial_s\mu \\ v_n &= -\Omega\partial_s j \end{aligned}$$

Triple Line
Equilibrium contact angle $\theta = \theta_0$

Linear peturbations $h = h_* + \delta h$
$\partial_t \delta h \sim \partial_{xxxx}\delta h$
Relaxation time of small perturbations
$t \sim L^4$



Liquid-state Dewetting

Polymer film (PDMS/Si)

G. Reiter et al PRL2000,2001, Fetzer et al

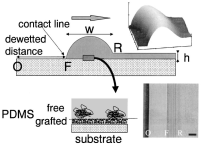


FIG. 1. Schematic representation of the experimental setup. A typical shape of the rim, as measured by atomic force microscopy, is shown in the upper right corner. The size of the image is 60 × 60 × 0.4 μm^3. Note that the lateral scale is about a factor of 100 larger than the vertical scale. In the lower right corner we show an optical micrograph representing the top view corresponding to the scheme. The length of the bar equals 50 μm.

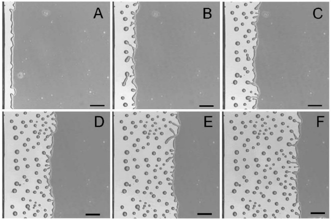
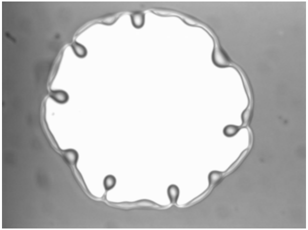


FIG. 2. Typical optical micrographs for the droplet formation at the later stages of the retraction of a 90 nm thin PDMS film (1000 Pa · s) at 130 °C on a silicon wafer coated with a 6 nm grafted PDMS layer for A: 60; B: 190; C: 310; D: 510; E: 690; and F: 870 sec, respectively. The length of the bar is 100 μm.



Liquids: viscosity and substrate friction

Viscous dissipation under shear $\dot{\gamma} = \partial_y v_x + \partial_x v_y$

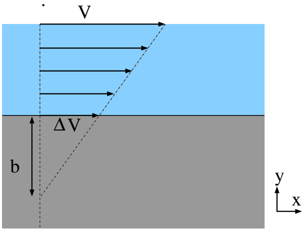
$$dQ \sim \eta \dot{\gamma}^2 dV$$

Continuity of tangential stress Navier 1823

$$\eta \partial_y v|_{wall} = \lambda \Delta v \quad \rightarrow \quad \Delta v = b \partial_y v|_{wall}$$

Slip length

$$\ell_s = \frac{\eta}{\lambda}$$



ℓ_s is usually small!
Link to wetting: hydrophobic ⇒ depletion ⇒ b increases
$\ell_s \sim (1 + \cos\theta)^{-2}$ D. M. Huang, *et al* Phys. Rev. Lett. 101, 226101 (2008)
at max tens of nm for water on atomically flat hydrophobic surfaces

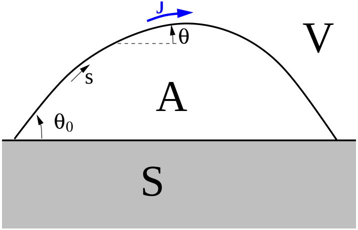
Hydrodynamics, lubrication Model

Local pressure variation $\Delta p = \tilde{\gamma}\kappa$.
Lubrication Model $\partial_x h \ll 1$, viscosity η, slip length ℓ_s

$$j = -\frac{1}{\eta\Omega}(h^3/3 + \ell_s h^2)\partial_x \Delta p$$
$$\partial_t h = -\Omega \partial_x j$$
$$\partial_t h = -\frac{\gamma}{\eta}\partial_x[(h^3/3 + \ell_s h^2)\partial_{xxx} h]$$

Triple Line
Equilibrium contact angle $\theta = \theta_0$

Linear peturbations $h = h_* + \delta h$
$\partial_t \delta h \sim \partial_{xxxx} \delta h$
Relaxation time of small perturbations
$t \sim L^4$



Generalized Model predictions 1D & small slopes

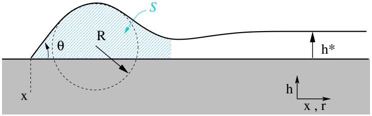
$$\partial_t h = \partial_x [h^n \partial_{xxx} h]$$

Scaling $\theta \ll 1$

$$\partial_{xx} h \sim \frac{1}{R} \quad h \sim R\theta^2 \quad x \sim R\theta$$

Triple line velocity

$$v = \frac{1}{\theta}\partial_t x_0 = \frac{1}{\theta}\partial_x [h^n \partial_x \frac{1}{R}] \sim \frac{\theta^{2n-3}}{R^{3-n}}$$



Mass conservation

$$\partial_t \mathcal{S} = v h^* \quad \rightarrow \quad \theta^3 \partial_t R^2 \sim \frac{\theta^{2n-3}}{R^{3-n}} h^*$$

$$\mathcal{S} \quad \sim \quad hL \sim R^2\theta^3$$

Asymptotic scaling

$$R \quad \sim \quad \theta^{-2(3-n)/(5-n)} h_*^{1/(5-n)} t^{1/(5-n)}$$

$$x_0 \quad \sim \quad \theta^{(3+n)/(5-n)} h_*^{-(3-n)/(5-n)} t^{2/(5-n)}$$

Multi-scale expansion / Example: $n = 0$, solid-state dewetting

Wong, Vorrhees, Miskis, Davis (2000)

small slope limit $\partial_x h \ll 1$
Mullins model

$$\begin{aligned} \partial_t h &= -\partial_{xxx} h \\ h(x_0(t)) = 0, \quad \partial_x h = \tan\theta = \alpha, & \quad \partial_x^3 h(x_0(t)) = 0, \quad h(x \to \infty) = 1. \end{aligned}$$

normalized varibales

$$X = \alpha(x - x_0(t)), \quad Y = h, \quad T = \alpha^4 t, \quad b = \alpha^{-3}\frac{dx_0}{dt}.$$

Boundary conditions

$$Y(X=0) = 0, \quad \partial_X Y(X=0) = 1, \quad \partial_X^3 Y(X=0) = 0, \quad Y(X \to \infty) = 1.$$

Slow dynamics $Y = Y_0 + Y_1 + Y_2 + ...$, with $Y_{n+1} \ll Y_n$

$$\begin{aligned} \partial_X^4 Y_0 - b^3 \partial_X Y_0 &= 0 \\ \partial_X^4 Y_n - b^3 \partial_X Y_n &= -\partial_T Y_{n-1} \end{aligned}$$

Solve Y_n order by order and then impose no-flux condition

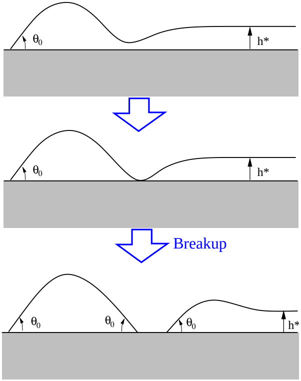
$$x_0(t) = \alpha\left(\frac{5t}{2\alpha}\right)^{2/5} - \frac{5}{4}\left(\frac{5t}{2\alpha}\right)^{1/5} + ...$$

Multi-scale expansion / Example: $n = 0$, solid-state dewetting

Asymptotic scaling

$$R \sim \theta^{-6/5} h_*^{1/5} t^{1/5}$$
$$x_0 \sim \theta^{3/5} h_*^{-3/5} t^{2/5}$$

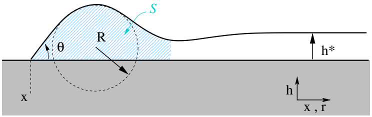
Mass shedding Wong, Vorrhees, Miskis, Davis (2000)



Multi-scale expansion / Example: $n = 2, 3$, liquid-state dewetting

Asymptotic scaling $n = 2$

$$\begin{aligned} R &\sim t^{1/3} \\ x_0 &\sim t^{2/3} \end{aligned}$$



Asymptotic scaling $n = 3$

$$\begin{aligned} R &\sim t^{1/2} \\ x_0 &\sim t \end{aligned}$$

No Mass shedding!

Rim instability

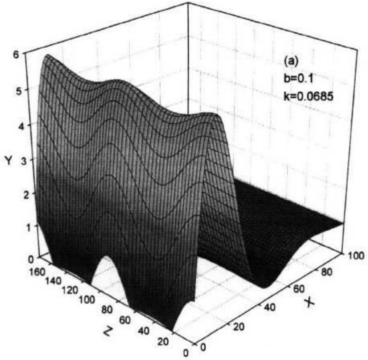
$$\partial_t h = \nabla \cdot [h^n \nabla \Delta h]$$

Transversal direction y, perturbation $q = 2\pi/\lambda$
Assuming $y \sim x$

$$\rightarrow q \sim \frac{1}{\theta R} \sim \frac{1}{\theta^{(n-1)/(5-n)} h_*^{1/(5-n)} t^{1/(5-n)}}$$

$n = 0 \rightarrow \lambda \sim t^{1/5}$
$n = 2 \rightarrow \lambda \sim t^{1/3}$
$n = 3 \rightarrow \lambda \sim t^{1/2}$

OPL 2013, Münch-Wagner 2014



Kan, Wong J.Appl. Phys. 2005

Final finger wavelength?

Wetting and dewetting of liquid and solid films

Lignes directrices

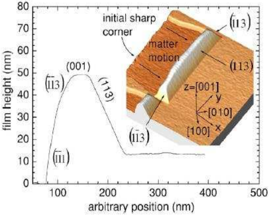
Evidences of facets on the rim

Ni(110)/MgO

J. Ye and C.V. Thompson, Acta Materialia 59, 582 (2011).

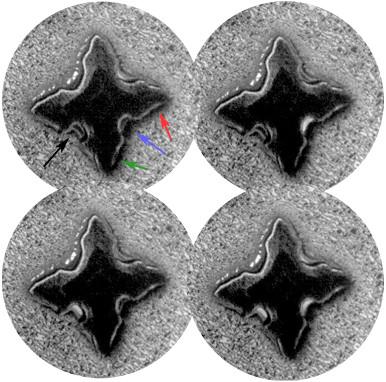
SOI (Si/SiO_2), AFM

Dornel Barbe Crecy Lacolle Eymery PRB2006



SOI (Si/SiO_2), LEEM

E. Bussman et al, New J. Phys. 2011



DEWETTING WITH FACETS?

Nucleation barrier

Dynamics limited by peeling or nucleation

Combe, Jensen, Pimpinelli, Phys Rev Lett 2000

Mullins and Rohrer, J. Am. Ceram. Soc. 2000

Cost: $2\pi\rho\gamma_{step}$

Gain: $\pi\rho^2\Delta\mu$ per atom, with $\Delta\mu = E_S/h$

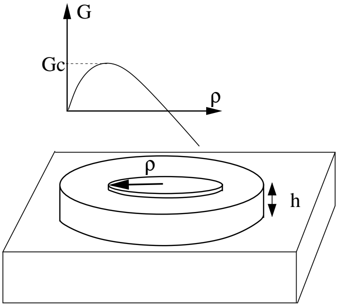
Total:

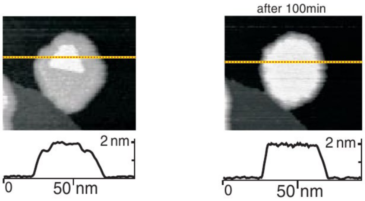
$$G = \gamma_{step} 2\pi\rho - \frac{E_S}{\Omega h}\pi\rho^2$$

$$G_c = \Omega\pi\frac{\gamma_{step}^2 h}{E_S}$$

$$\mathcal{I} = \rho_0\Gamma_{+c}\left(\frac{-a^4\partial_{ss}G_c}{2\pi T}\right)^{1/2} \mathrm{e}^{-G_c/T},$$

Slow relaxation time $t \sim \mathrm{e}^{G_c/k_B T}$





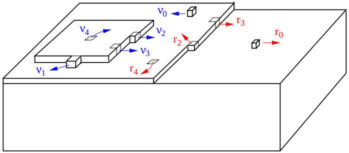
Experiments Ice/Pt(111)

Thurmer, Bartelt P.R.L. 2008

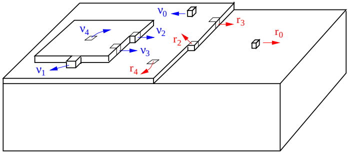
Lignes directrices

SOS KMC model

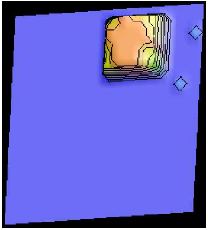
- KMC simulations SOS Hopping rates
  A/S: $r_n = \nu_0 \, \mathrm{e}^{-nJ/T + E_S/T}$
  A/A: $\nu_n = \nu_0 \, \mathrm{e}^{-nJ/T}$
  J bong energy; E_S substrate contact energy ($= \Delta + \gamma_{100}$)



SOS KMC model

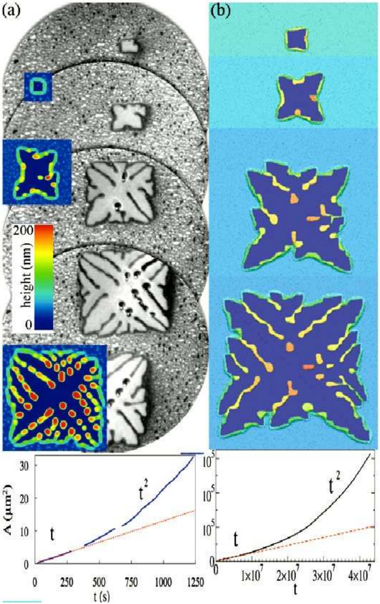


- KMC simulations SOS Hopping rates
  A/S: $r_n = \nu_0\, \mathrm{e}^{-nJ/T+E_S/T}$
  A/A: $\nu_n = \nu_0\, \mathrm{e}^{-nJ/T}$
  J bong energy; E_S substrate contact energy $(= \Delta + \gamma_{100})$

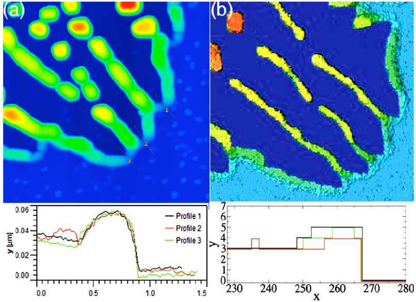


- Equilibrium shape Low temperatures:
  $h = E_S^{2/3} J^{-2/3} N^{1/3}$; $h/L = E_S/J$
  $E_S = 1$, $N = 900$, $\to h = 8.7$, simul at $T/J = 0.35$

KMC vs SOI



$h = 3,\ E_S = 1,\ T = 0.5$



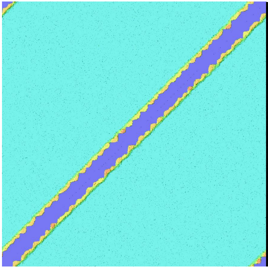
SOI system LEEM Experiments:

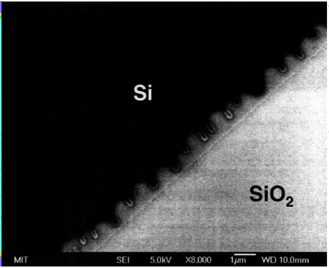
E. Bussman, F. Leroy, F. Cheynis, P. Müller

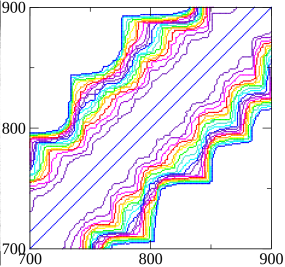
11 fronts

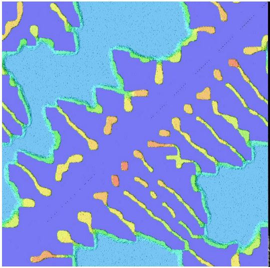
$h = 3,\ h_1 = 9,\ T = 0.5,\ E_S = 1.5,$

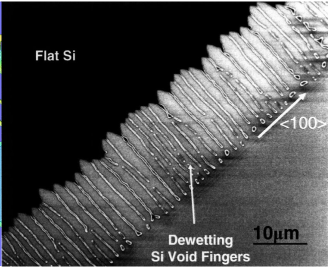
Danielson PhD Thesis, MIT 2008





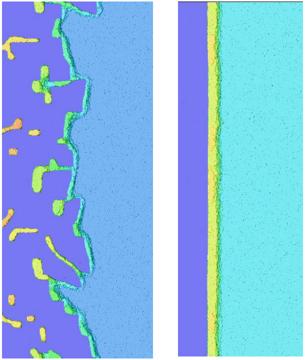


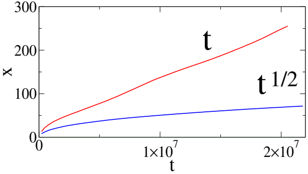




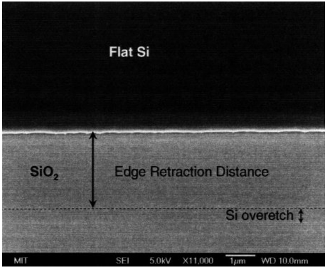
10 fronts: Metastability?

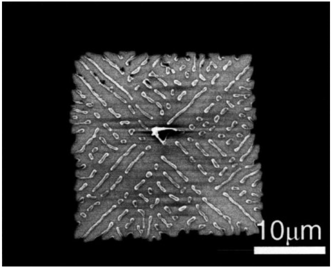
KMC





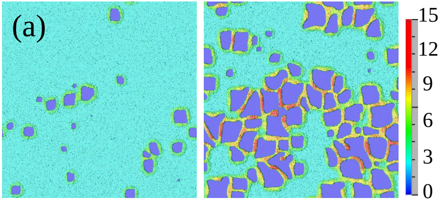
Danielson PhD Thesis, MIT 2008

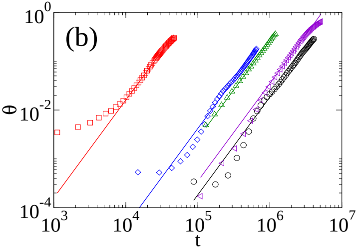




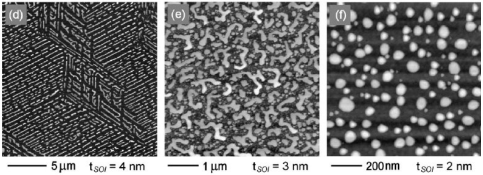
Dewetting of a complete film

$h = 3,\ E_S = 0.7,\ T = 0.5$





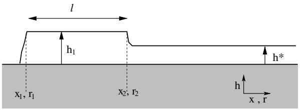
Burhanudin et al Surf. Sci 2006



hole radius $R \sim t^{1/2}$
hole area $A \sim R^2 \sim t$
uncoverage $\theta \sim t^2$

Lignes directrices

Facetted rim



Diffusion-limited dynamics

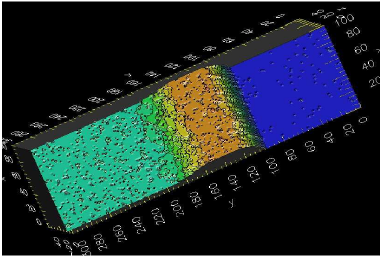
two fronts: $x_1(y,t)$, and $x_2(y,t)$
rim height h_1

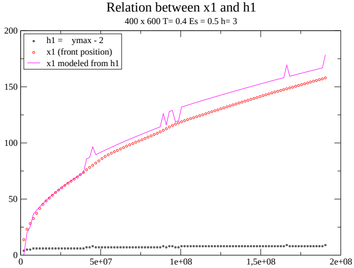
$$\begin{aligned} h_1 v_{n1} &= -a^2 D\mathbf{n}\cdot\nabla c|_1 + (x_2 - x_1)\partial_t h_1 \\ (h_1 - h)v_{n2} &= -a^2 D\mathbf{n}\cdot\nabla c|_2 \\ D\Delta c &= 0 \end{aligned}$$

$c_1 = c_{eq}\mathrm{e}^{E_S/Th_1}$, $c_2 = c_{eq}$

Straight front

$$\begin{aligned} \sigma &= \mathrm{e}^{E_S/Th_1} - 1 \\ H_1 &= (h^{-1} - h_1^{-1})^{-1} \\ x_1 &= \frac{C}{h} + (2a^2 D c_{eq})^{1/2} H_1 \left(\int_{t_0}^{t} dt' H_1' \sigma'\right)^{1/2} \end{aligned}$$





Layer-by-layer thickening of the rim

Nucleation + Zipping process

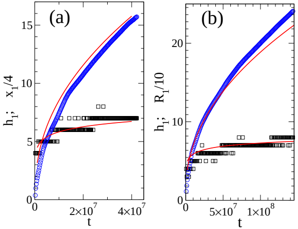
$$\partial_t h_1 = (V_{zip}\mathcal{J})^{1/2}$$

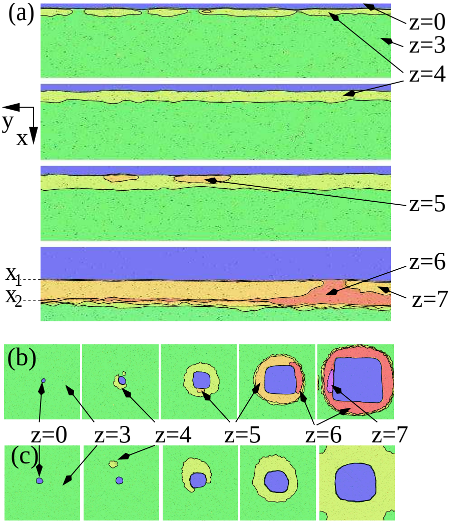
$$\mathcal{J} = \ell \frac{Dc_{eq}}{a^2} \frac{E_S^{3/2} T^{1/2}}{\pi\gamma^2 a^2 h_1^{3/2}} \mathrm{e}^{-\pi\gamma^2 a^2 h_1 / TE_S}$$

$$V_{zip} \sim a^2 Dc_{eq}\kappa \left(\frac{E_S}{Th_1} - \frac{a^2\gamma\kappa}{T} \right)$$

$$V_{zip} \approx C_{zip} a^2 Dc_{eq} \frac{E_S^2}{a^2 Th_1^2 \gamma}$$

C_{zip} unknown number

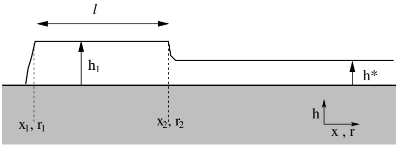




Facetted rim dynamics

Surface diffusion on top facet:

$$\begin{aligned} \Delta\mu &= \frac{E_S}{h_1} \\ \partial_t x_1 &\sim \frac{\Delta\mu}{\ell} \\ \ell(h_1 - h^*) &= x_1 h^* \\ \Rightarrow x_1 &\sim t^{1/2} h_1^{-1/2} \end{aligned}$$



We recover the previous law:
$\ell \sim h_1 \Rightarrow h_1 \sim x_1^2 \Rightarrow x_1 \sim t^{2/5}$

Facetted rim

$$\begin{aligned} \partial_t h_1 \sim \mathrm{e}^{-G_c} &\sim \mathrm{e}^{-\Omega\pi\gamma_{step}^2 h_1/E_S} \\ \Rightarrow h_1 &\sim \ln t \\ \Rightarrow x_1 &\sim t^{1/2}(\ln t)^{-1/2} \end{aligned}$$

Asymptotics

Facetted rim

$$x_1(t) \sim t^{1/2}(\ln t)^{-1/2}$$
$$h_1 \sim \ln t$$
$$\ell \sim t^{1/2}(\ln t)^{-3/2}$$

Recall continuum model

$$x_0(t) \sim t^{2/5}$$
$$R \sim t^{1/5}$$

Distinguish $\ln t$ from $t^{1/5}$??
Si/SiO_2 Leroy et al $x \sim t^{1/3}$
Metal GH Kim et al $x \sim t^{2/5}$.

Instability of a facetted rim: Linear Coarsening

Lin. stab. anal. - non-steady-state:

$x_1(t,y) = x_1(t) + x_1^{(1)}(t,q)$

$x_2(t,y) = x_2(t) + x_2^{(1)}(t,q)$

x_1 unstable, x_2 stable

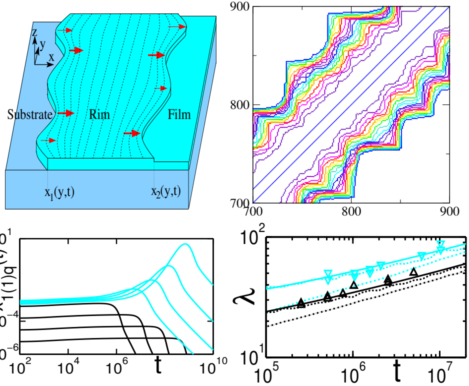
limit $q\ell \gg 1$

$$x_1^{(1)}(t,q) \sim \exp[a(t)q - b(t)q^3]$$
$$x_2^{(1)}(t,q) \sim \exp[-a(t)q - b(t)q^3]$$

Mode of largest amplitude

$$\lambda_{max} \approx 2\pi \left(\frac{3\int_0^t dt' \tilde{\gamma}_1 h_{1(0)}^{-1}(t')}{\int_0^t dt' E_S h_{1(0)}^{-2}(t') \ell_{(0)}^{-1}(t')} \right)^{1/2} .$$

- (110) -rough orientation $\tilde{\gamma}_1 \approx \gamma$ constant
  Coarsening: $\lambda \sim t^{1/4} (\ln t)^{-1/2}$
  Numerical power-law fit $\lambda \sim t^{0.2}$



Instability of a facetted rim: Linear Coarsening

Lin. stab. anal. - non-steady-state:

$x_1(t,y) = x_1(t) + x_1^{(1)}(t,q)$

$x_2(t,y) = x_2(t) + x_2^{(1)}(t,q)$

x_1 unstable, x_2 stable

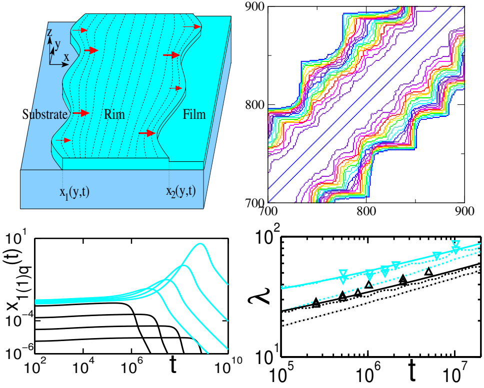
limit $q\ell \gg 1$

$$x_1^{(1)}(t,q) \sim \exp[a(t)q - b(t)q^3]$$
$$x_2^{(1)}(t,q) \sim \exp[-a(t)q - b(t)q^3]$$

Mode of largest amplitude

$$\lambda_{max} \approx 2\pi \left(\frac{3\int_0^t dt' \tilde{\gamma}_1 h_{1(0)}^{-1}(t')}{\int_0^t dt' E_S h_{1(0)}^{-2}(t') \ell_{(0)}^{-1}(t')} \right)^{1/2} .$$

- (110) -rough orientation $\tilde{\gamma}_1 \approx \gamma$ constant
  Coarsening: $\lambda \sim t^{1/4}(\ln t)^{-1/2}$
  Numerical power-law fit $\lambda \sim t^{0.2}$
- (100) -vertical (100) facet
  $\tilde{\gamma}_1 = Ta/\beta^2 \approx (T/2a)e^{\gamma h_1/T}/h_1$
  Stable

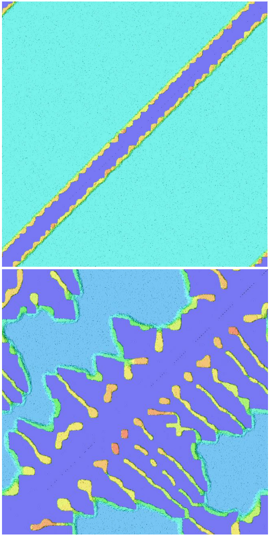


Rim Breakup

KMC

$$t_B \sim E_S^{-2.8} h^{4.2}, \quad \lambda_B \sim E_S^{-1.0}\ h^{1.2}.$$

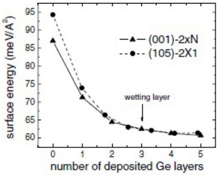
Conjecture: λ_B si the finger width?



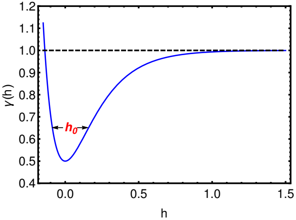
Wetting and dewetting of liquid and solid films

Wetting potential

- Short range electronic effects
  Wetting potential Ge/Si G.-H. Lu and F. Liu, PRL, 94 176103 (2005)



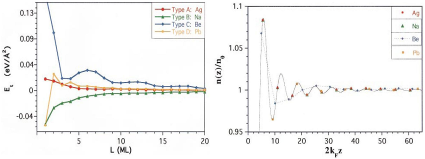
Short range repulsive
+ Long range attractive

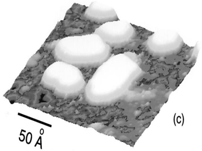


- Van der Waals interactions
  $W_{vdW}(h) = -A/(12\pi h^2)$
  Hamaker constant $|A| \sim 10^{-19}$J
  attraction/repulsion

- Electronic confinement in metals → Magic thickness

Z. Zhang et al, Phys.Rev.Lett.1998,1999





Wetting potential

Credits

- Liquids
  see Quéré, Brochard, De Gennes book, or Safran book
- Wetting potential stabilizing wetting film for various instabilities
  Golovin et al PRB 2004, Levine et a PRB 2007, Aqua et al PRB 2007
- Hole formation with anisotropy
  Khenner PRB 2008
- Nano-island Ostwald ripening
  L. Golubovic et al PRE 2013

Question: Consequences of wetting potential on wetting/dewetting dynamics?

Lignes directrices

Continuum model with Wetting potential

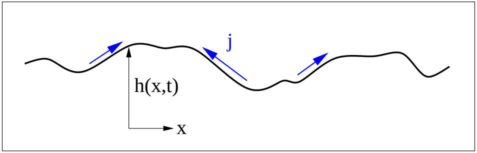
Substrate at $h = 0$
Free energy per unit area :

$$\gamma(h) = \gamma_\infty + \mathcal{W}(h)$$

Wetting potential $\mathcal{W}(h) \to 0$ as $h \to \infty$

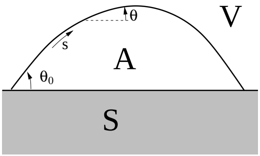
$$\begin{aligned} \mu(x) &= -\gamma_\infty \partial_{xx} h + \gamma'(h) \\ \mathbf{j} &= -\mathcal{M}(h) \nabla \mu \\ \partial_t h &= -\nabla \cdot \mathbf{j} \end{aligned}$$

Far from the substrate: $h \to \infty$
$\mathcal{M}(h) \to \mathcal{M}_\infty$
$\gamma(h) \to \gamma_\infty$



Lignes directrices

Non-equilibrium boundary condition



Equilibrium condition at Triple Line
Young-Dupré
$\gamma \cos\theta_{eq} + \gamma_{int} = \gamma_{sub}$

Liquids
P.G. de Gennes
Grain Boundaries
U. Czubayko et al, Acta Mater. (1998); M. Upmanyu et al Acta Mater. (2002).
Solid-state wetting
Wang, Jiang, Bao, Srolovitz (2015)

$$v = K(\cos\theta - \cos\theta_{eq})$$

Microscopic origin of the kinetic coefficients:

- Wetting potential?
- Microscopic Kinetic coefficients affected by the vicinity of substrate?

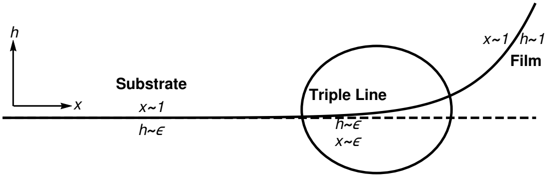
Is this the correction triple line BC?
Derive K from mesoscopic model?

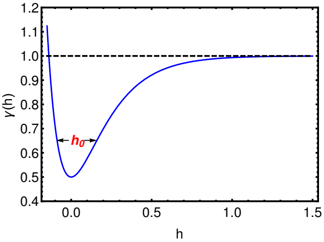
Matched asymptotic Expansion

- Expand in small parameter $\epsilon \sim h_0$

Matched asymptotic Expansion

- Expand in small parameter $\epsilon \sim h_0$

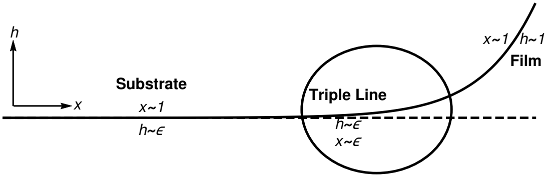


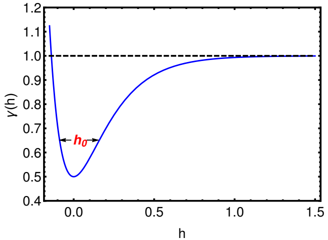


-

Matched asymptotic Expansion

- Expand in small parameter $\epsilon \sim h_0$





-

$$\text{(a)}\quad \text{Film region} \begin{cases} h \sim O(1) \\ x \sim O(1) \end{cases}$$

$$\text{(b)}\quad \text{TL region} \begin{cases} h = \epsilon H(X,t) \\ x = x_{TL} + \epsilon X \end{cases}$$

$$\text{(c) Substrate region} \begin{cases} h(x,t) = \epsilon \mathcal{H}(\chi,t) \\ \chi = x \end{cases}$$

-

Kinetic Boundary Conditions

To 0th order, Young & no-flux

$$\theta = \theta_{eq} \qquad \frac{\gamma_\infty}{2}\theta_{eq}^2 = \gamma_\infty - \gamma_{min} \qquad J = 0$$

... To 3rd order, KBC (Linear / Onsager)

$$\begin{bmatrix} \mathcal{L}_{2v} & \mathcal{L}_{1v} \\ \mathcal{L}_{1v} & \mathcal{L}_{1J} \end{bmatrix} \begin{bmatrix} v \\ J \end{bmatrix} = \begin{bmatrix} [U] \\ -[\mu] \end{bmatrix} \approx \begin{bmatrix} \gamma_\infty(\cos\theta - \cos\theta_{eq}) \\ -\gamma_\infty\kappa + h_{sub}\gamma''_{min} \end{bmatrix}$$

Kinetic Boundary Conditions

To 0th order, Young & no-flux

$$\theta = \theta_{eq} \qquad \frac{\gamma_\infty}{2}\theta_{eq}^2 = \gamma_\infty - \gamma_{min} \qquad J = 0$$

... To 3rd order, KBC (Linear / Onsager)

$$\begin{bmatrix} \mathcal{L}_{2v} & \mathcal{L}_{1v} \\ \mathcal{L}_{1v} & \mathcal{L}_{1J} \end{bmatrix} \begin{bmatrix} v \\ J \end{bmatrix} = \begin{bmatrix} [U] \\ -[\mu] \end{bmatrix} \approx \begin{bmatrix} \gamma_\infty(\cos\theta - \cos\theta_{eq}) \\ -\gamma_\infty \kappa + h_{sub}\gamma''_{min} \end{bmatrix}$$

- Thermodynamic Fluxes :
  v : velocity of triple line
  J : mass flux through triple line

Kinetic Boundary Conditions

To 0th order, Young & no-flux

$$\theta = \theta_{eq} \qquad \frac{\gamma_\infty}{2}\theta_{eq}^2 = \gamma_\infty - \gamma_{min} \qquad J = 0$$

... To 3rd order, KBC (Linear / Onsager)

$$\begin{bmatrix} \mathcal{L}_{2v} & \mathcal{L}_{1v} \\ \mathcal{L}_{1v} & \mathcal{L}_{1J} \end{bmatrix} \begin{bmatrix} v \\ J \end{bmatrix} = \begin{bmatrix} [U] \\ -[\mu] \end{bmatrix} \approx \begin{bmatrix} \gamma_\infty(\cos\theta - \cos\theta_{eq}) \\ -\gamma_\infty\kappa + h_{sub}\gamma''_{min} \end{bmatrix}$$

- Local Thermodynamic Potentials :

$$U = -\frac{\gamma_\infty}{2}(\partial_x h)^2 + \gamma(h).$$
$$\mu = -\gamma_\infty \partial_{xx} h + \gamma'(h),$$

- Thermodynamic Fluxes :
  - v : velocity of triple line
  - J : mass flux through triple line

Kinetic Coefficients

$$\begin{bmatrix} \mathcal{L}_{2v} & \mathcal{L}_{1v} \\ \mathcal{L}_{1v} & \mathcal{L}_{1J} \end{bmatrix} \begin{bmatrix} v \\ J \end{bmatrix} = \begin{bmatrix} [U] \\ -[\mu] \end{bmatrix}$$

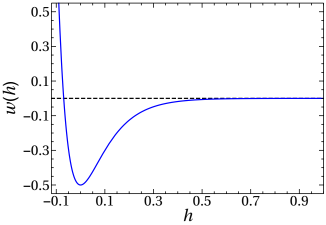
Kinetic coefficients

$$\begin{aligned} \mathcal{L}_{1J} &= \int_{-\infty}^{\infty} dX \left(\frac{1}{M(H_0)} - \frac{\Theta(X)}{M(\infty)} - \frac{\Theta(-X)}{M(0)} \right) \sim \frac{\epsilon}{M} \\ \mathcal{L}_{1v} &= \int_{-\infty}^{\infty} dX \left(\frac{H_0}{M(H_0)} - \Theta(X) \frac{X \partial_x h_0(x_{TL})}{M(\infty)} \right) \sim \frac{\epsilon^2}{M} \\ \mathcal{L}_{2v} &= \int_{-\infty}^{\infty} dX \left[\frac{H_0^2}{M(H_0)} - \frac{\Theta(X)}{M(\infty)} (X \partial_x h_0(x_{TL}))^2 \right] \sim \frac{\epsilon^3}{M} \end{aligned}$$

In most cases $\theta \sim \theta_{eq}$?

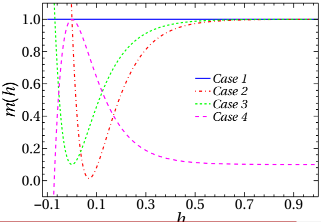
Numerical simulations

Wetting potential

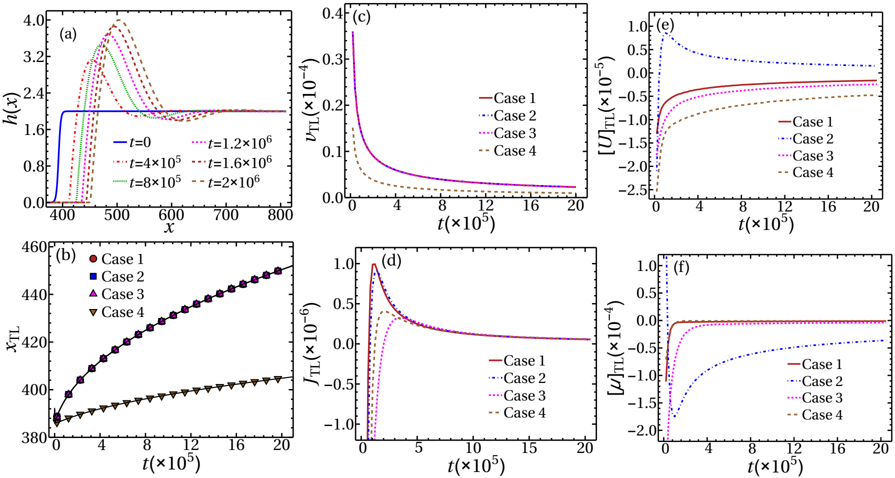


Mobility

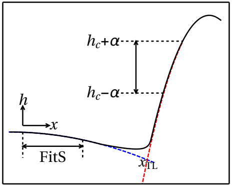
- case 1 constant mobility
- case 2 reduced mobility in the triple line region
- case 3 asymmetric: lower mobility in the substrate
- case4 asymmetric: lower mobility in the film

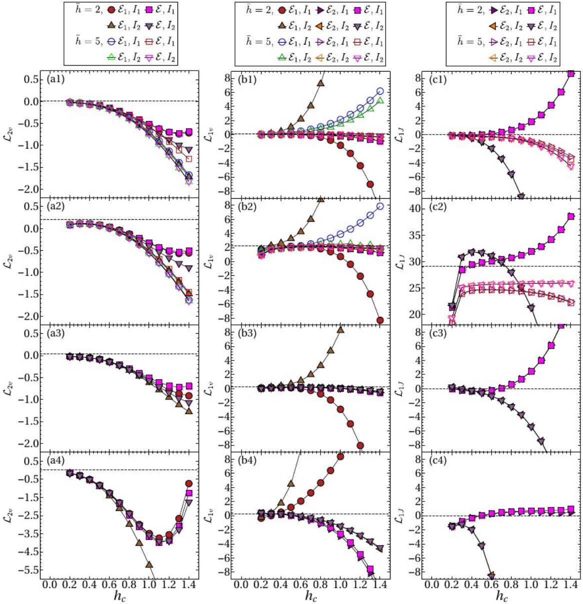


Numerical simulations



Numerical simulations



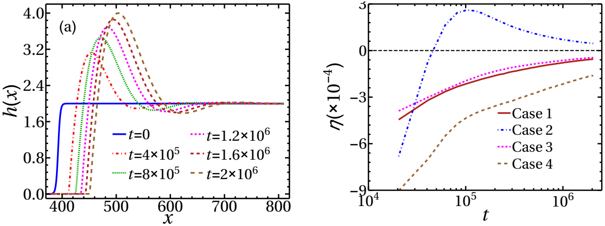


Numerical simulations

Dynamic constact angle θ_D

$$\eta = \frac{\theta_{eq} - \theta_D}{\theta_{eq}}$$

Dewetting dynamics



Summary on Kinetic Boundary Condition

- 2 Kinetic Boundary Conditions for v and J
- Numerical validation
- Convergence of kinetic coefficients.
  $W(h) - W(\infty) \sim h^{-n}$, with $n > 3$
  $M(h) - M(\infty) \sim h^{-m}$, with $m > 3$
  Van der Waals $n = 2$??

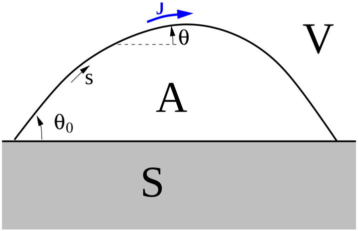
Lignes directrices

Surface Diffusion Mullins' Model

Mullins model $\mu = \Omega\tilde{\gamma}\kappa$

$$j = -\frac{Dc}{k_B T}\partial_s \mu$$
$$v_n = -\Omega \partial_s j$$

$v_n \sim \partial_{ss}\kappa$
Equil. contact angle $\theta = \theta_0$



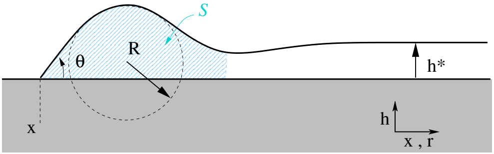
Dewetting dynamics

Wong, Voorhees, Miskis, Davis, Acta Mater. 2000

Brandon and Bradshaw

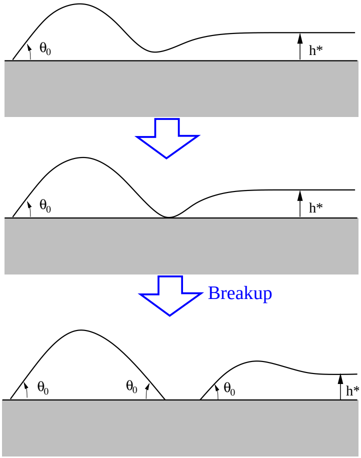
Small slopes $\theta \ll 1$
$\lambda \sim \theta R$, and $h \sim \theta^2 R$

$$\partial_t x = \theta^{-1} v_n \sim \theta^{-1}\partial_{ss}\kappa \sim \theta^{-1}\lambda^{-2}R^{-1}$$
$$\mathcal{S} \sim h\lambda \sim R^2\theta^3$$
$$\partial_t \mathcal{S} = v\bar{h}$$
$$h \sim \theta^{4/5}\bar{h}^{1/5}t^{1/5}$$
$$x \sim \theta^{3/5}\bar{h}^{-3/5}t^{2/5}$$



Mass shedding

Wong, Voorhees, Miskis, Davis, Acta Mater. 2000



Scaling solution $\bar{h} \sim \theta^{4/5} \bar{h}^{1/5} T^{1/5}$

$$T_c^{WV} = a \frac{\bar{h}^4}{\theta_0^4}; \qquad a \approx 2 \times 10^5.$$

Wong, Voorhees, Miskis, Davis, Acta Mater. 2000

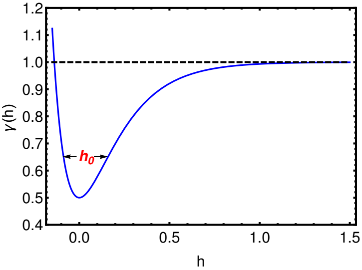
Numerical Simulation

Wetting Potential

$$\gamma(h) = \gamma_\infty + \mathcal{W}(h)$$
$$\mathcal{W}(h) = (\gamma_\infty - \gamma_{min})(\mathrm{e}^{-h/h_0} - 2\mathrm{e}^{-h/2h_0})$$

$h_{min} = 0; \quad \gamma(h_{min}) = \gamma_{\mathrm{min}}$.
Young Contact angle:

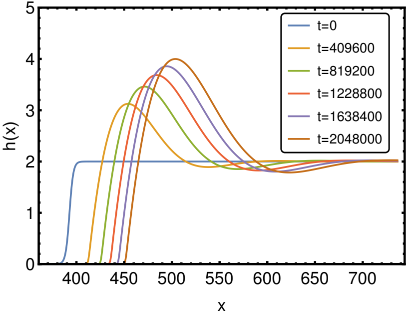
$$\gamma_\infty \cos(\theta_0) = \gamma_{min}$$

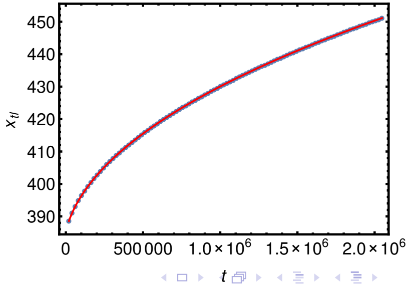


Film profile

Dewetting from film edge
$\theta_0 = 10^o$ and $h_0 = 0.05$
Quantitative agreement with Wong-Voorhees

$$x_{tl}(t) = x_0 + at^{1/5} + bt^{2/5}$$

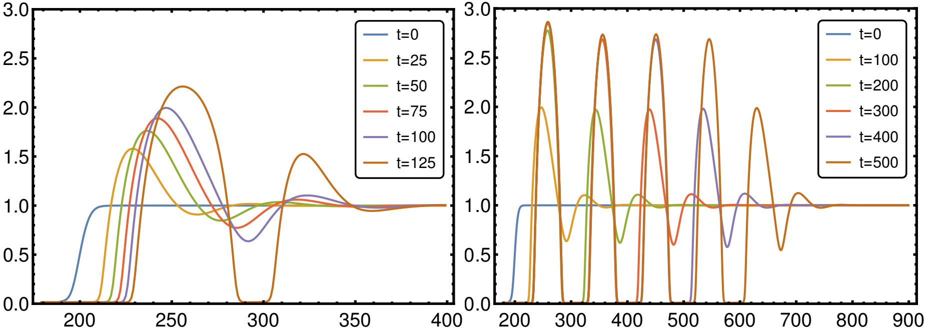




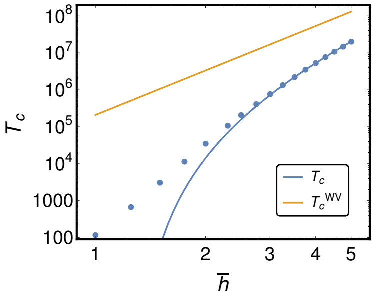
Mass Shedding

Periodic Mass shedding

$\theta_0 = 60^o$ and $h_0 = 0.1$



Accelerated Mass shedding



- without wetting potential:
  Wong and Voorhees solution $\bar{h} \sim \theta^{4/5}\bar{h}^{1/5}T^{1/5}$

$$T_c^{WV} = a\frac{\bar{h}^4}{\theta_0^4}; \qquad a \approx 2 \times 10^5.$$

- with wetting potential $\mathcal{W}(h)$:
  Mass shedding accelerated by orders of magnitude

Cutoff height h_{cut} within WV solution: $\bar{h} - h_{cut} \sim \theta^{4/5}\bar{h}^{1/5}T^{1/5}$

$$T_c = A_1\frac{(\bar{h} - h_{cut})^5}{\theta_0^4\bar{h}}$$

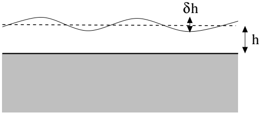
With $A_1 = 1.5 \times 10^5$, and $h_{cut} = 1.2$

Small thicknesses: spinodal dewetting

Linear stability analysis : $h = \bar{h} + \delta h$
$\delta h \sim \mathrm{e}^{i\omega t + iqx}$

$$i\omega = \mathcal{M}(\bar{h})\, q^2[-\gamma_\infty q^2 + W''(\bar{h})]$$

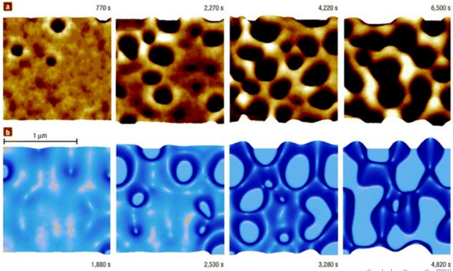
Spinodal Instablility if $W''(\bar{h}) \leq 0$



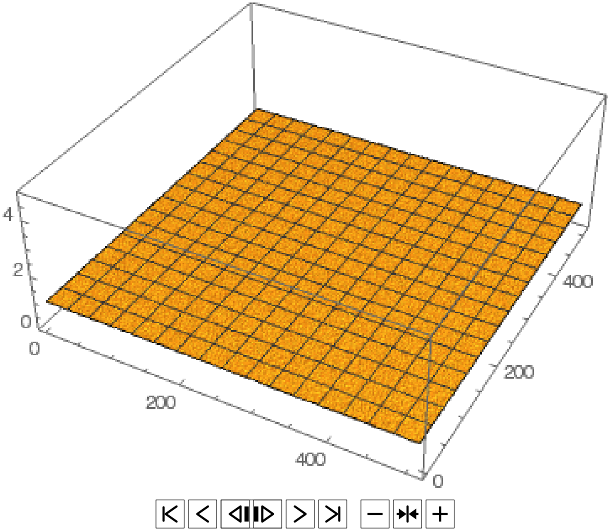
$$\lambda_{LS} = \frac{2^{3/2}\pi\bar{\gamma}^{1/2}}{W''(\bar{h})^{1/2}}$$

$$T_{LS} = \frac{4\bar{\gamma}}{\bar{\mathcal{M}}W''(\bar{h})^2}$$

Liquids



Embedded Animation

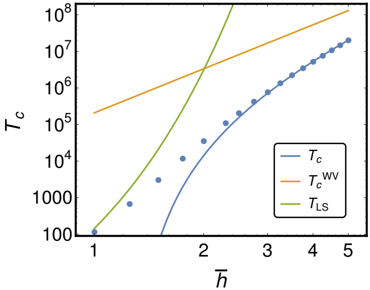


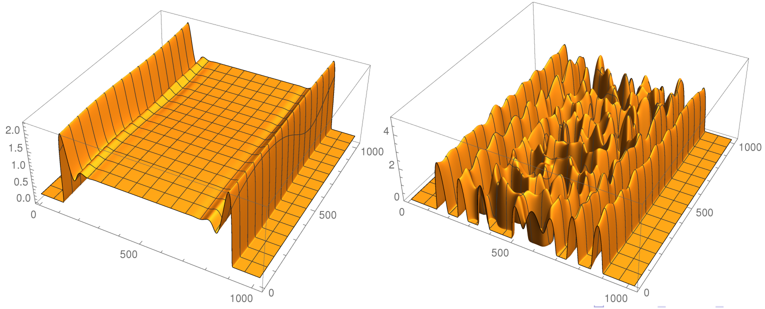
Ashwani Tripathi, ILM-Lyon

Small thicknesses: spinodal dewetting

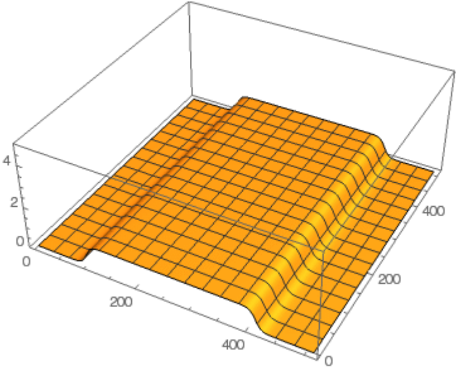
Linear stability analysis : $h = \bar{h} + \delta h$
Spinodal Instablility if $W''(\bar{h}) \leq 0$

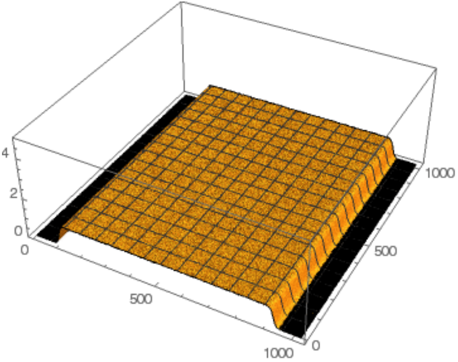
$$T_{LS} = \frac{4\bar{\gamma}}{\bar{\mathcal{M}} W''(\bar{h})^2}$$





Accelerated mass shedding





Ashwani Tripathi, ILM-Lyon

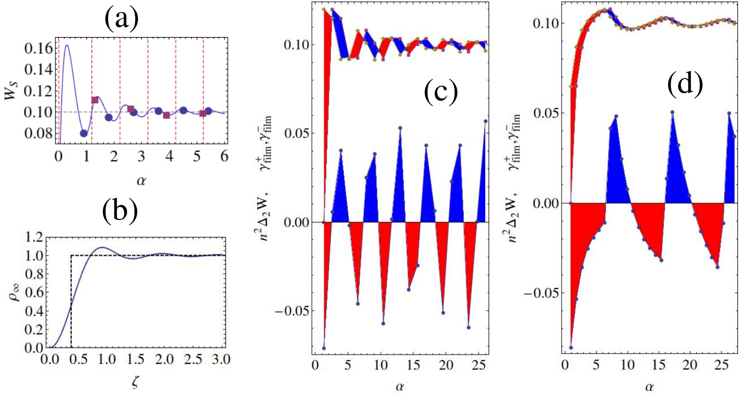
Lignes directrices

Electronic Quantum confinement

Free electron model

$$W_{EC}(h) \approx -\frac{E_{fb}}{(h+2b)^2}\frac{\pi}{36\sqrt{3}}\cos(2k_{fb}h)$$

E_{fb}, k_{fb} Fermi energy and wavevect,
$b = 3\pi k_{fb}/8$

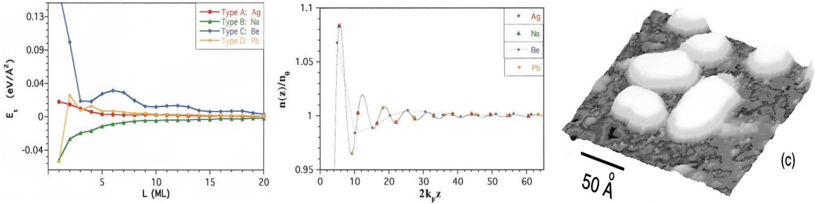


(a) Al(111) (purple squares), Ag(111) (blue circles)
(c) Al(111) ,(d) Ag(111) blue-Stable, red-Unstable

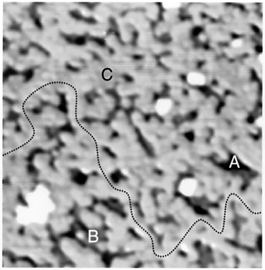
Magic heights and labyrinthine patterns

Metals/ semicon or insulator: Electronic confinement $\rightarrow$ Magic thickness

Z. Zhang et al, Phys.Rev.Lett.1998,1999



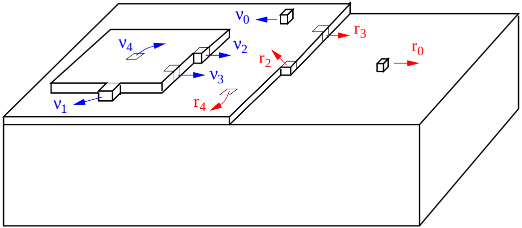
Experiments Ag/Si(111)



SOS KMC model with magic height

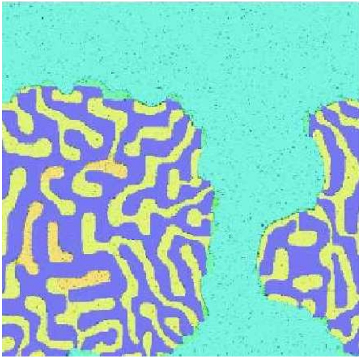
KMC simulations SOS

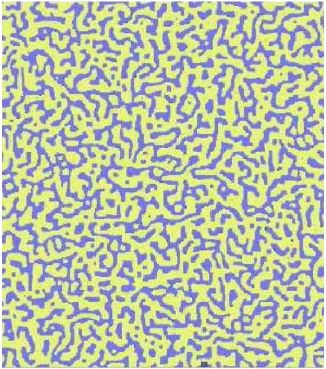
$$
\begin{aligned}
z \neq 1 \text{ and } z \neq h_* \qquad & \nu_n = \nu\,\mathrm{e}^{-(nJ+J_0)/T} \\
z = 1 \qquad & r_n = \nu\,\mathrm{e}^{-(nJ+J_0-E_S)/T} \\
z = h_* \qquad & r_n^* = \nu\,\mathrm{e}^{-(nJ+J_0-E_*)/T}
\end{aligned}
$$



KMC simualtions with magic height

A. Chame, OPL, Phys Rev B 2014





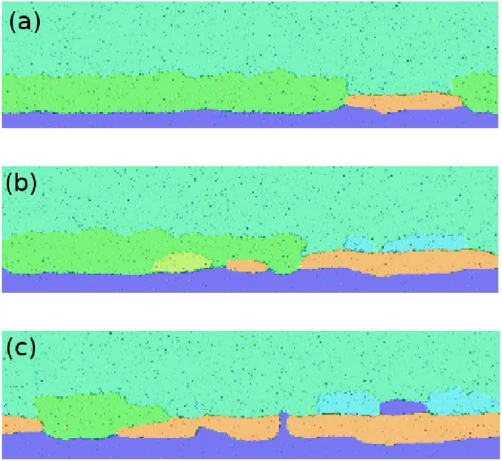
$\lambda \sim$ 30nm
Semi-quantitative agreement with experiments

Magic-height rim

800×800, $T = 0.4$, $h = 3$, $E_S = 0.4$, $h_* = 7$, $E = -0.5$

Induced nucleation and incomplete closure

A. Chame, OPL, Phys Rev B 2014



Lignes directrices

Conclusion

Consequences of the wetting potential:

- Triple line kinetics: 2 Boundary Conditions
  A. Tripathi, OPL, preprint 2016
- Attractive part in the wetting potential → accelerated mass shedding
  A. Tripathi, OPL, preprint 2016
  - Decreasing thickness: VW, cutoff height, Linear spinodal instability
- Quantum Magic height → rim breakup and labyrinthine patterns
  A. Chame, OPL, Phys Rev B 2014
  - Incomplete rim closure
  - Induced hole nucleation behind the rim

Co-authors:
Dr. Ashwani Tripathi, postdoc, ILM-Lyon 1, France
Prof. Anna Chame, UFF, Rio, Brazil
Prof. Yukio Saito, Keio, Japan
K. Takano, Univ. Keio, Japan
P. Smereka†, Univ-Michigan, Ann Harbor, USA
P. Gaillard, ILM, Lyon, France
M. Ignacio, ILM, Lyon, France

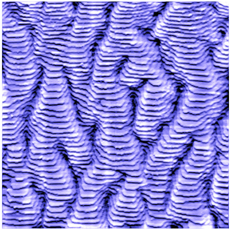
Funding: ANR Grant *Nanomorphogénèse* and *DéFiS* and *LOTUS*, CNRS, and CNPQ-Brazil

Wetting and dewetting of liquid and solid films

Lignes directrices

Growth shapes

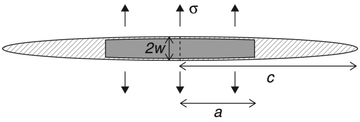
Snowflake Yoshi Furukawa, Hokkaido, Japan



Growth Cu(1,1,17) Maroutian, Ernst, Saclay, France

Force of crystallization and rims

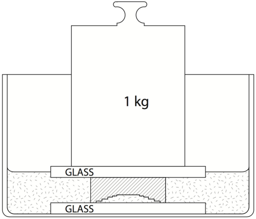
Weathering, aging of building material e.g. cements



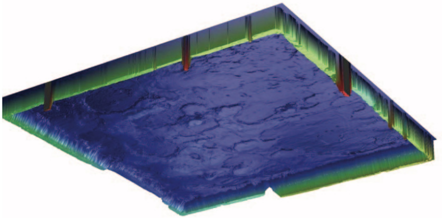
A. Ryne, P. Meakin, A. Malthe-Srenssen, B. Jamtveit and D. K. Dysthe EPL 96 (2011)

Espinoza-Marzal et al Accounts of Chem. Res. (2009)

Force of crystallization and rims



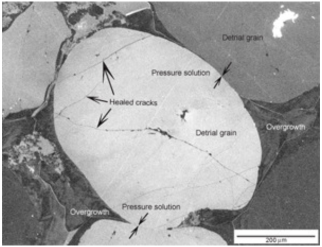
becker and Day, 1916



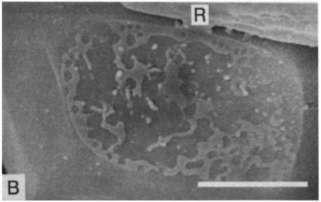
A. Røyne PhD Thesis UiO

Pressure solution

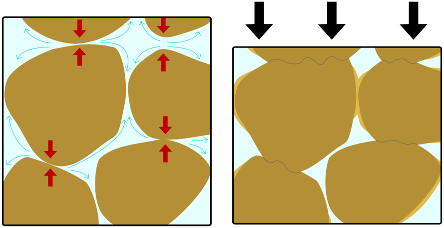
Rock compaction, weathering, aging of building material e.g. cements



Univ. Bern http://www.geo.unibe.ch/

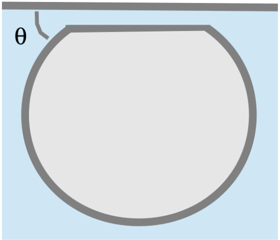


Quartz aggregates at high temperatures S.F. Cox and M.S. Paterson



Equilibrium Wetting state

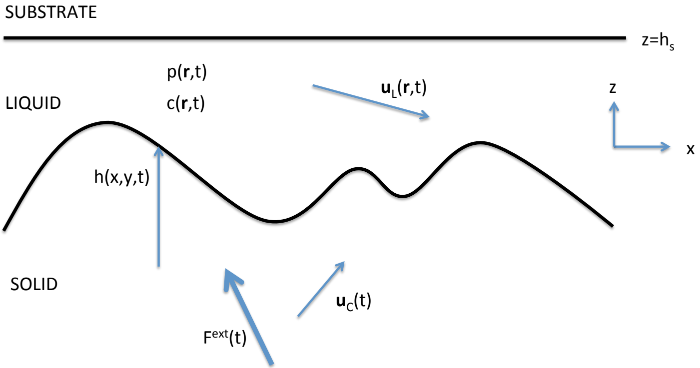
Equilibrium of an immersed solid in a liquid $\sim$ Wetting
Equilibrium Contact angle: $\gamma_\infty \cos\theta = \gamma_{min}$



Lignes directrices

Strategy

Dynamics at contacts → Thin film approach



Film thickness

$$\zeta(x, y, t) = h_s - h(x, y, t).$$

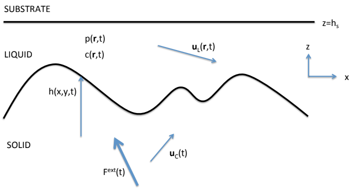
Assumptions

Model ingredients

- Mass transport
  - diffusion in liquid D
  - Hydrodynamics / viscosity η
- Force / energy
  - Force $\mathbf{F}_C$ on a rigid solid
  - surface tension $\gamma(\mathbf{n})$
  - Interaction potential $U(\zeta)$, disjoining pressure $U'(\zeta)$

Basic assumptions

- Small slopes: $|\nabla h| \ll 1$
- Liquid always present $\zeta > 0$
- Rigid solid, no rotation, translation along z

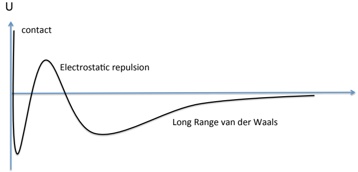


More on interactions

Ingredients in the interaction potential:

- Electrostatic $U(\zeta) \sim \exp[-\zeta/\lambda_D]$
- van der Waals $U(\zeta) \sim -A/\zeta^2$
- Hydration $U(\zeta) \sim \exp[-\zeta/\lambda]$
- liquid ordering, solute effects, etc.

DLVO (electrosctatics + van der Waals)



Thin film model

Lubrication lumit $|\nabla h| \ll 1$

Global mass conservation

$$\rho_C(\partial_t \zeta + u_{Cz}) = -\rho_L \nabla_{xy} \cdot \left[\frac{\zeta^3}{12\eta} \nabla_{xy} p\right] + \rho_L \partial_t \zeta$$

Conservation of crystal molecules

$$-\frac{\partial_t \zeta + u_{Cz}}{\Omega} + \partial_t[\zeta c_{eq}] - \nabla_{xy} \cdot \left[\frac{\zeta^3}{12\eta} c_{eq} \nabla_{xy} p\right] = \nabla_{xy} \cdot [\zeta D \nabla_{xy} c_{eq}].$$

Local equil. conc. $c_{eq} = c_0 \mathrm{e}^{\Delta\mu/k_B T}$ with

$$\frac{\Delta\mu(x,y,t)}{\Omega} = -\tilde{\gamma}_1 \partial_{x_1 x_1} h - \tilde{\gamma}_2 \partial_{x_2 x_2} h - U'(\zeta) + (\frac{\rho_C}{\rho_L} - 1)p$$

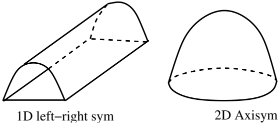
Force balance

$$F_{Cz} = \iint_{\text{contact}} \mathrm{d}A\,(p - p^{ext} + W'(h))$$

Unknowns: $p(x,y,t)$, $\zeta(x,y,t)$, $u_{Cz}(t)$

Lignes directrices

A Simple case



Assumptions

- Geometry: axisymetric (2D), or ridge $x \to -x$ (1D)
- Equal densities $\rho_L = \rho_C$
- Dilute limit $\Omega c \ll 1$
- Linear thermodyn $\Delta\mu \ll k_B T$

Evolution equation, axisymetric case

$$\partial_t \zeta + u_{Cz} = -D_e \frac{1}{r} \partial_r \left[r\zeta \partial_r (\gamma \partial_{rr} \zeta + \frac{\gamma}{r} \partial_r \zeta - U'(\zeta)) \right]$$

$$D_e = \frac{D\Omega^2 c_0}{k_B T}.$$

Force balance

$$u_{Cz} \int_0^R 2\pi r \mathrm{d}r \int_r^R \mathrm{d}r' \, \frac{6\eta r'}{\zeta(r')^3} = F_{Cz}^{2D} + 2\pi \int_0^R \mathrm{d}r \, rU'(\zeta)$$

Viscous force | Disjoining force

Steady-states

$$0 = u_{Cz} + D_e \frac{1}{r}\partial_r \left[r\zeta \left(\gamma\partial_{rr}\zeta + \frac{\gamma}{r}\partial_r\zeta - U'(\zeta) \right) \right]$$

Large forces
→ flat contact
→ small curvature
→ negligible surface tension effects
→ Analytical solution

Steady-states

γ terms negligible in the contact

Repulsive potential

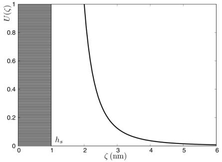
$$U(\zeta) = \frac{A}{\zeta^n}$$

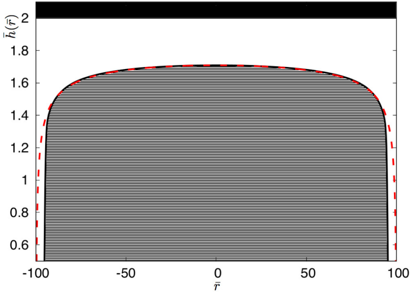
Crystal surface profile

$$\zeta(r) = \left(\frac{\zeta_0^n}{1 - r^2/R^2} \right)^{1/n}.$$

$$R^2 = \frac{4D_e(n+1)A}{\zeta_0^n u_{Cz}}$$

Full numerical solution
$n = 3$
BC: fixed c and ζ





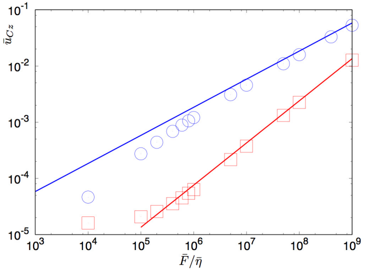
Steady-states

Force Balance

$$\frac{F_{Cz}^{2D}}{\pi R^2} = 12\eta \frac{n^2}{(2n+3)(n+3)} \left(\frac{1}{D_e A(n+1)}\right)^{\frac{3}{n}} \left(\frac{R^2}{4} u_{Cz}\right)^{\frac{n+3}{n}}$$
$$+ \frac{n^2}{2n+1} A^{-\frac{1}{n}} \left(\frac{1}{D_e(n+1)}\right)^{\frac{n+1}{n}} \left(\frac{R^2}{4} u_{Cz}\right)^{\frac{n+1}{n}}$$

Viscous force $\bar{\eta} = 1$
Disjoining force $\bar{\eta} = 10^3$

$$\bar{\eta} = \frac{D_e}{\lambda^2}\eta = \frac{D\Omega^2 c_0}{\lambda^2 k_B T}\eta$$



$$u_{Cz}^{2D} \sim R^{-\frac{4n+2}{n+1}} (F_{Cz}^{2D})^{\frac{n}{n+1}}$$
$$u_{Cz}^{2D} \sim R^{-\frac{4n+6}{n+3}} \left(\frac{F_{Cz}^{2D}}{\eta}\right)^{\frac{n}{n+3}}$$

Steady-states

Power-law repulsive potential

- "flat" profile
- dissolution velocity increases with load (power-law)
- Similar results 1D & 2D axisym

Orders of Magnitude

- Calcite
  - ζ scale $\sim$ nm
  - x scale $\sim$ 10nm
  - t scale $\sim 10^{-1}$ s
  - p scale $\sim$ MPa
  - η scale $\sim 10^{2}$ Pa s
- Salts ($NaCl0_3$)
  - ζ scale $\sim$ nm
  - x scale $\sim$ 1 to 10nm
  - t scale $\sim 10^{-6}$ s
  - p scale $\sim$ MPa
  - η scale $\sim 10^{-2}$ Pa s

Steady-states

γ terms neglected in the contact

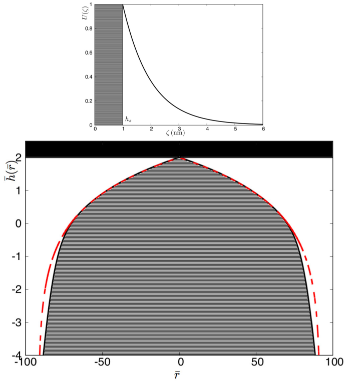
Repulsive potential finite

$$U(\zeta) \quad = \quad A\mathrm{e}^{-\zeta/\lambda}$$

Pointy conical shape

$$\zeta_{sing} \approx 2^{1/2}\frac{\lambda}{R}|r|$$

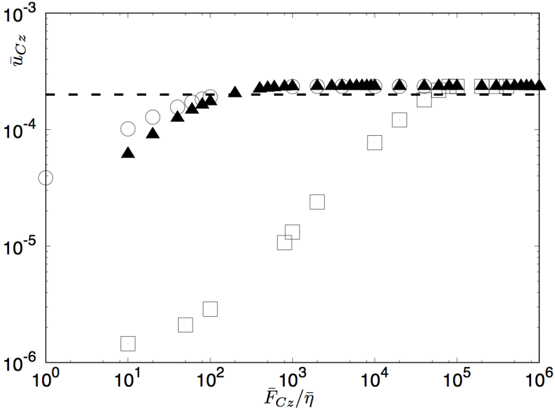
Complete solution: no contact



Steady-states

Constant velocity!

$$u_{Cz}^{2D} = D_e \frac{4A}{R^2}$$



$\bar{\eta} = 5 \times 10^2, 5 \times 10^{-1}, 5 \times 10^{-4}$

Steady-states

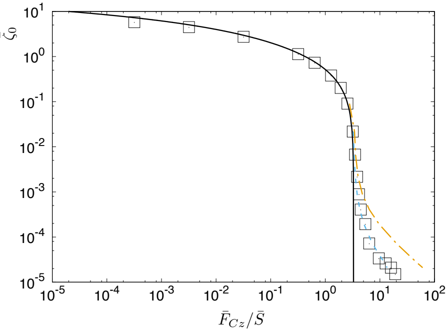
Force Balance

$$\frac{F_{Cz}^{2D}}{\pi R^2} = \Big[12\eta D_e \frac{A}{\lambda^3}\psi(\frac{\zeta_0}{\lambda})\frac{e^{\frac{\zeta_0}{\lambda}}}{1+\frac{\zeta_0}{\lambda}} + \frac{A}{4\lambda}(\frac{2\zeta_0}{\lambda}+1)\frac{e^{-\frac{\zeta_0}{\lambda}}}{1+\frac{\zeta_0}{\lambda}}\Big]$$

$$\lim_{z\to 0}\psi(z) = (1-\ln 2)\,.$$

Finite Force four touching contact $\zeta_0 = \zeta(0) = 0$

$$F_c^{2D} = \Big[12\eta D_e \frac{A}{\lambda^3}(1-\ln(2)) + \frac{A}{4\lambda}\Big]\pi R^2$$



Origin of deviation at small ζ_0?

Steady-states

Line tension effect

$$0 = u_{Cz} + D_e \frac{1}{r}\partial_r \left[r\zeta \left(\gamma \partial_{rr}\zeta + \frac{\gamma}{r}\partial_r\zeta - U'(\zeta) \right) \right]$$

Taylor expand

$$\zeta^{tip} = \zeta_0 + \frac{r^2}{2}\partial_{rr}\zeta_0$$

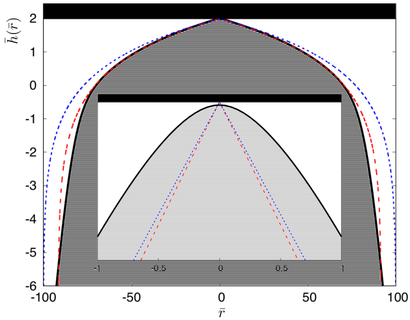
Diverging viscous contribution

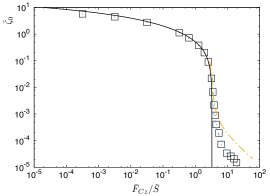
$$F_{\text{tip}}^{2D} = \eta \frac{6\pi u_{Cz}}{(\partial_{rr}\zeta_0)^2\zeta_0}$$

Matched asymptotic analysis:
$\partial_{rr}\zeta_0 \to$ cst when $\zeta_0 \to 0$

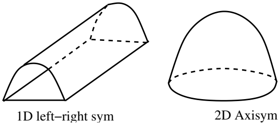
$$F_{\text{tip}}^{2D} = \frac{24\pi\eta\gamma^2 D_e \lambda^2}{C_{2D}^2 A R^2} \frac{1}{\zeta_0}$$

$C_{2D} \approx 0.015$



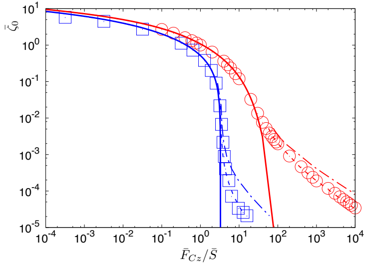


1D vs 2D



- 2D touching contact without γ
- 1D log div. no contact without γ: $F_{Cz} \sim \ln[1/\zeta_0]$

but similar regularization of tip by surface tension



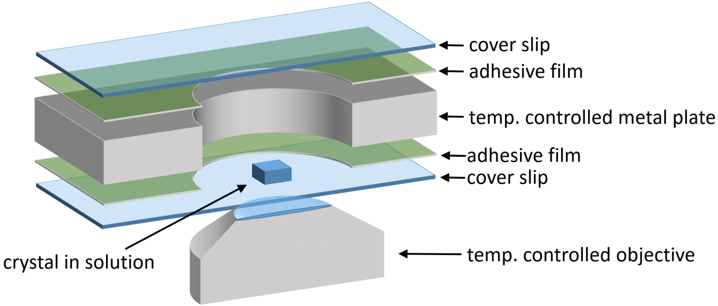
Steady-states

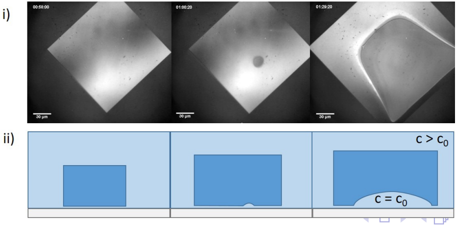
- 2D (touching contact without γ) vs 1D (log div. no contact without γ) but similar regularization by surface tension
- Interactions control contact shapes and dissolution rates in pressure solution
  - flat vs pointy
  - increasing with load vs constant
- Experiments: Need of single-contact measurements (SFA/AFM)
- Rock compaction problem: interaction between contacts

Lignes directrices

Experimental setup

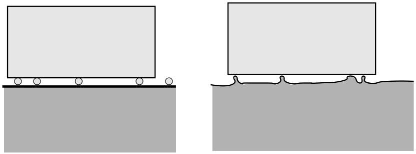
Felix Kohler and Dag Kristian Dysthe, UiO, Norway





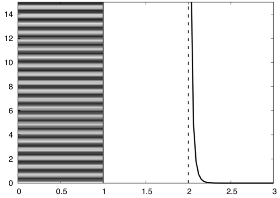
Model

Experiments:
$\zeta \sim$ 10 to 100nm
Interaction: Roughness or (nano)particles !



Thin film Model
Potential (Yukawa-like)

$$U(\zeta) = A\frac{e^{\frac{-(\zeta-\zeta_c)}{\lambda\zeta_c}}}{\zeta-\zeta_c},$$



Simulations

Boundary conditions:

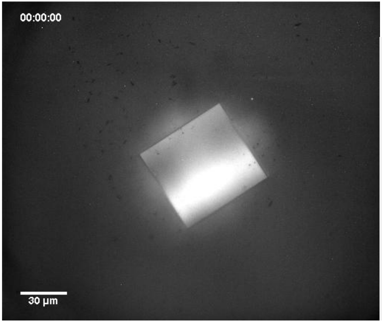
- Fixed thickness ζ_b at the boundaries
- Fixed supersaturation at the boundaries

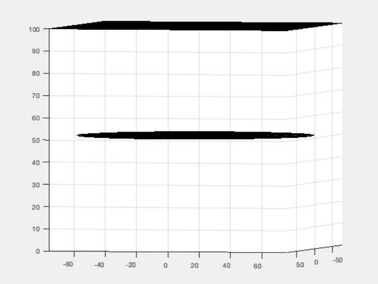
Force: weight

$$F_{Cz} = (\rho_C - \rho_L) g L^3$$

Simulate facet?
$\rightarrow$ diverging stiffness $\tilde{\gamma} = \gamma + \gamma''$

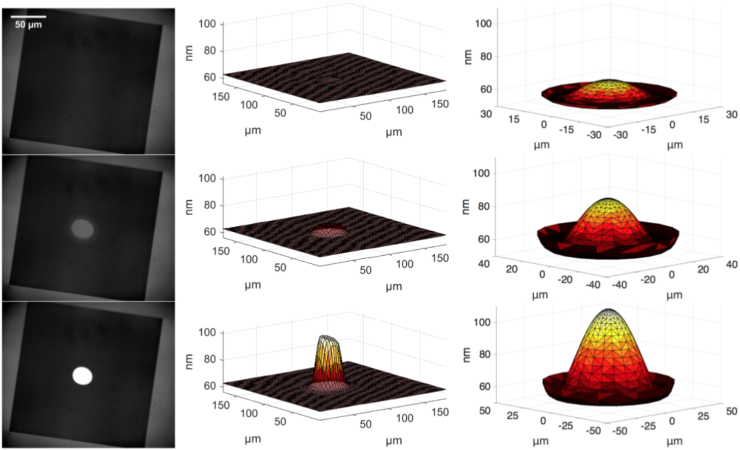
Experiments vs Theory



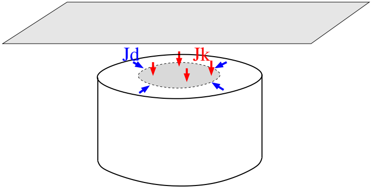


Experiments: growth in fixed supersaturation
Simualtion: growth for a contact with a fixed size

Summary of observations



Heuristics



Mass balance / Axisymetric geometry

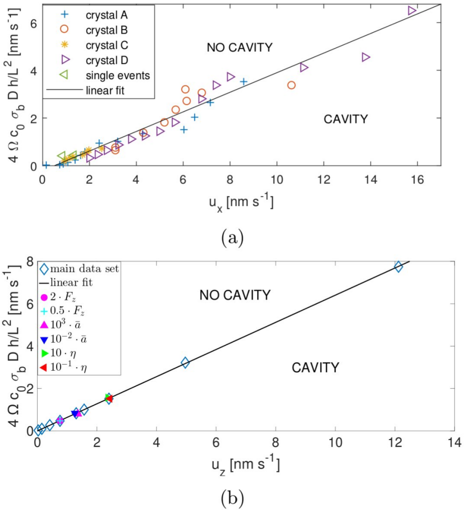
$$\begin{aligned} \pi r^2 J_k &= 2\pi r \zeta_c J_d(r) \\ \pi r^2 \frac{u_{Cz}}{\Omega} &= -2\pi r \zeta_c D \frac{dc}{dr}, \\ \frac{u_{Cz}}{4\Omega}\left(L^2 - r^2\right) &= \zeta_c D(c(L) - c(r)) \end{aligned}$$

Cavity formation criterion: $c(r=0) \leq c_0$

$$u_{Cz} \geq 4\Omega c_0 \sigma_b D \frac{\zeta_c}{L^2}$$

$\sigma_b = c(L)/c_0 - 1$

Non-equilibrium phase diagram



Experiments (a) & Theory (b)

Linear pre-factor < 1

u_{cz} vs u_{Cx}

Assumption $\tilde{\gamma} \sim 10^2 \mathrm{Jm}^{-2}$

No influence of

- force / weight, potential amplitude
- BC thickness ζ_b
- viscosity

Lignes directrices

Conclusion

Summary:

- Derivation of a thin film lubrication model for dissolution/growth + confinement
- Pressure solution of a single contact
  Depends on the repulsive potential profile
- Confined growth
  Cavity formation: initial stage of growth rims

Funding: Nanoheal Marie-Curie ETN

Wetting and dewetting of liquid and solid films

- Deweting of solid films:

OPL, A. Chame, Y. Saito, Phys Rev Lett 2007

OPL, A. Chame, Y. Saito, Phys Rev Lett 2009

OPL, A. Chame, M. Dufay, EPJB 2010

M. Dufay, OPL, Phys Rev Lett 2011

E. Bussmann, F. Cheynis, F. Leroy, P. Müller, OPL, NJP, 2010

A. Chame, OPL Phys Rev E, 2011

A. Chame, OPL, C. R. Phys. 2013

A. Chame, OPL, Phys Rev B 2014

M. Trautmann, F. Cheynis, F. Leroy, S. Curiotto, O. Pierre-Louis, adn P. Mller Appl. Phys. Lett. 110, 263105 40 (2017)

A. Tripathi, OPL, preprint 2017

- Islands on nano-patterns: Multi-stability / Collapse / Elasticity

OPL, Y. Saito, Europhysics Letters 2009

M. Dufay, OPL, Phys Rev B, 2010

K. Takano, Y. Saito, OPL, Phys Rev B, 2010

P. Gaillard, Y. Saito, OPL, Phys Rev Lett 2011

M. Ignacio, Y. Saito, OPL, Phys Rev B 2012

Y. Saito, M. Ignacio, OPL, C. R. Phys. 2013

M. Ignacio, Y. Saito, P. Smereka, OPL, Phys Rev Lett 2014

M. Ignacio, OPL, Phys Rev E 2014

- Wetting of reactive islands

F. Leroy, Y. Saito, F. Cheynis, E. Bussmann, OPL, and P. Müller, Phys Rev B 2014

F. Leroy, Y. Saito, O. Pierre-Louis, S. Curiotto, F. Cheynis, O. Pierre-Louis, and P. Mller Appl. Phys. Lett. 106 191601 (2015)

- Immersed solids

L. Gagliardi, OPL, preprint 2017

Collaborators:
Prof. Y. Saito, Univ. Keio, Japan
K. Takano, Univ. Keio, Japan
Prof. A. Chame, UFF Rio, Brasil
P. Smereka, Univ-Michigan, Ann Harbor, USA
D. Margetis, Univ. Maryland, USA
D. Tanguy, ILM Lyon, France
M. Dufay, ILM, Lyon, France
P. Gaillard, ILM, Lyon, France
M. Ignacio, ILM, Lyon, France
A. Tripathi, ILM, Lyon, France
L. Gagliardi, ILM, Lyon, France
Experiments:
P. Müller group, Cinam, Marseille France
D.K. Dysthe group, UiO, Oslo, Norway

Funding: ANR PNANO *Nanomorphogénèse* and *DéFiS* and *LOTUS*, CNRS, CNPQ-Brasil, JSPS-Japan, Euro. Council (Marie-Curie)