Summer school on Epitaxy

MATEPI 2025

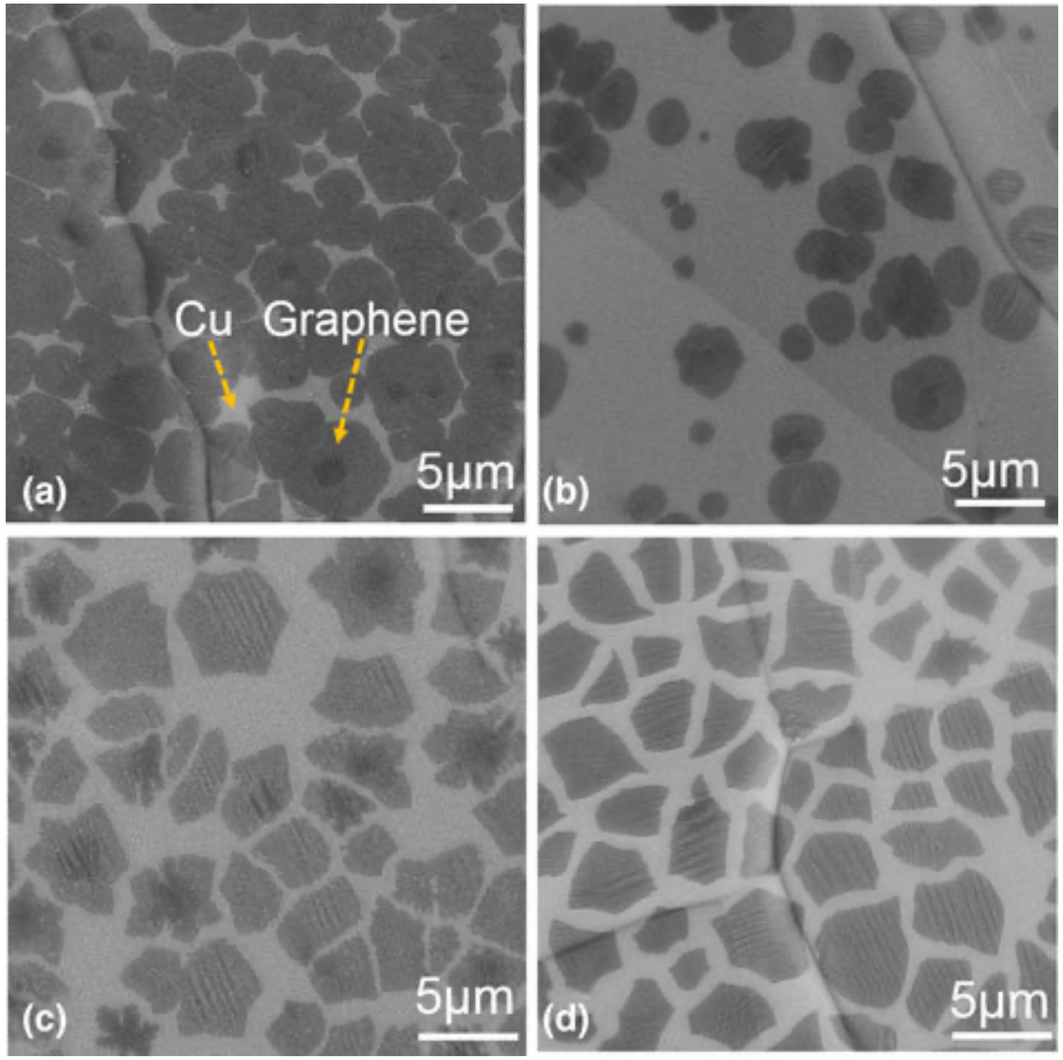
Porquerolles June 22-27 2025

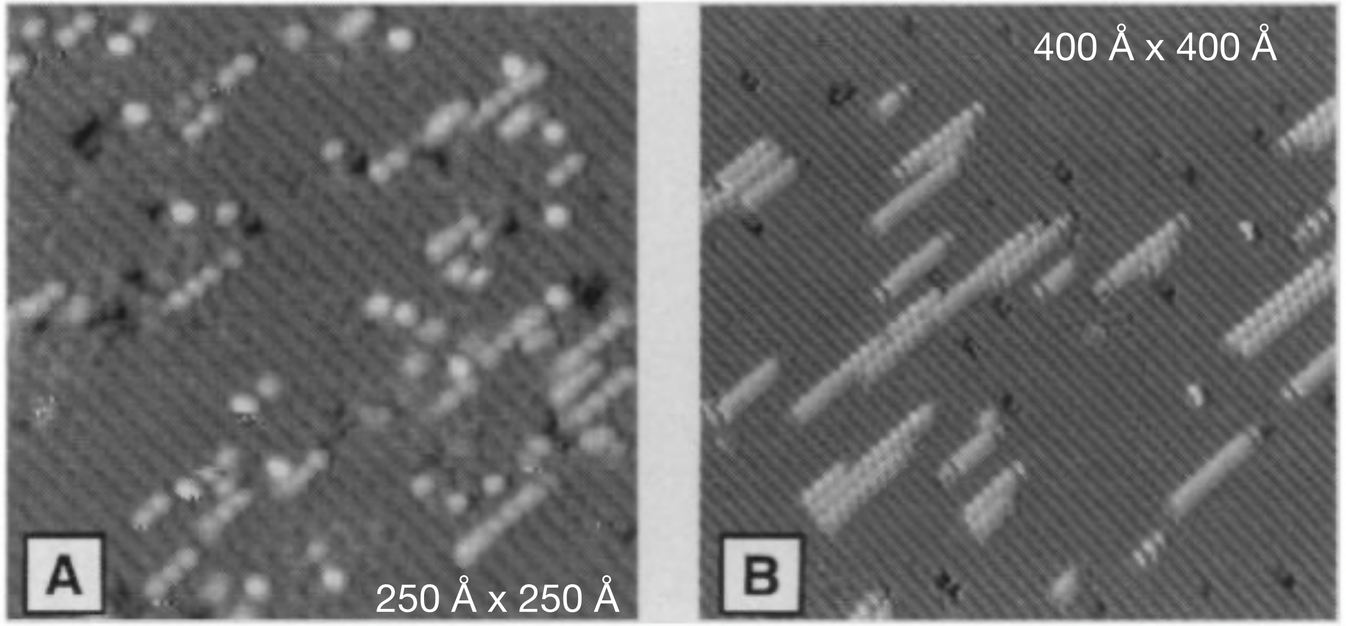
Alberto Pimpinelli

Université Clermont Auvergne

Clermont-Ferrand, France

Introduction to the Physics of Epitaxial Growth: nucleation

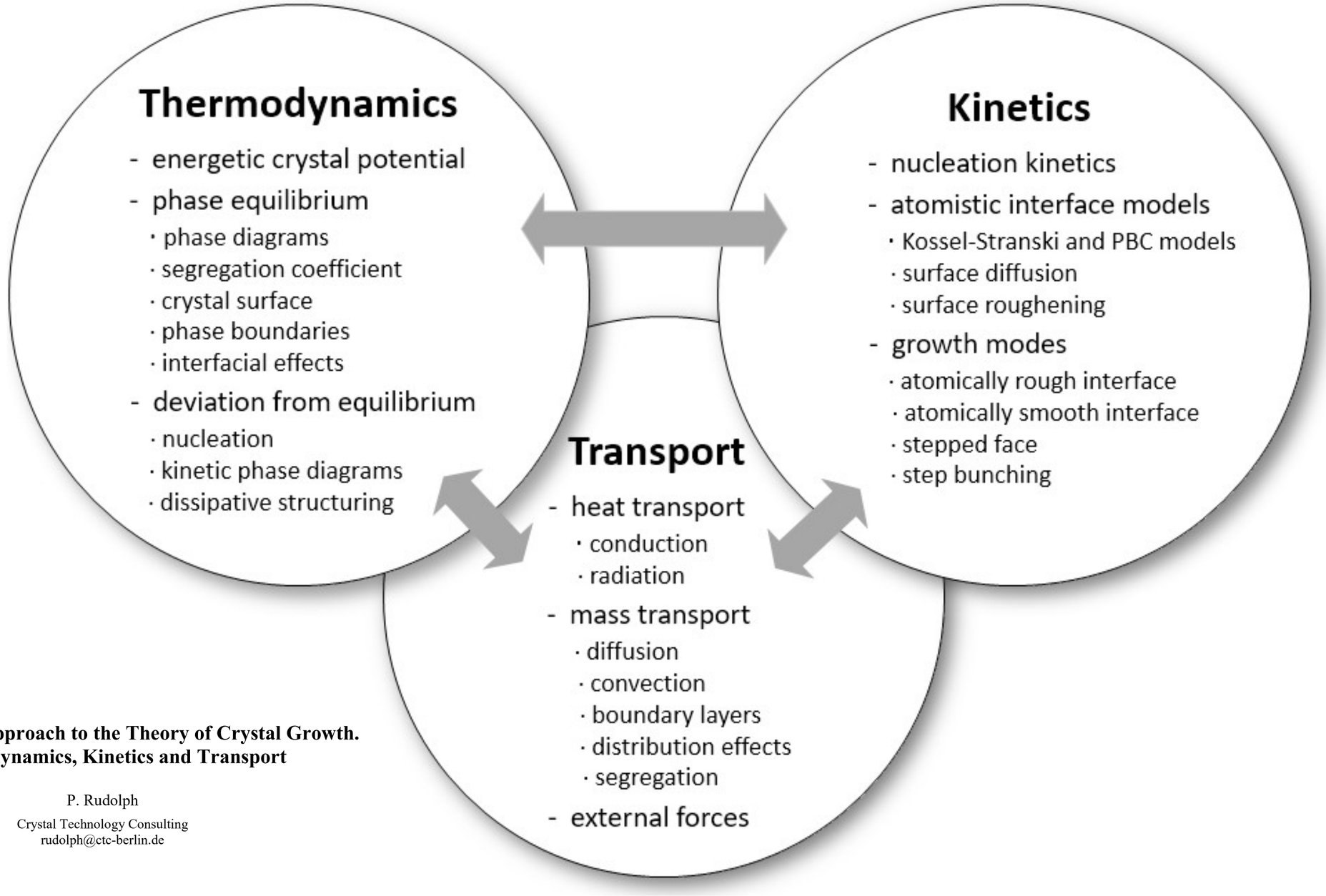




Atomistic Processes in the Early Stages of Thin-Film Growth
Science, Apr. 18, 1997, New Series, Vol. 276, No. 5311 (Apr. 18, 1997), pp. 377-383

Effect of intermittent oxygen exposure on chemical vapor deposition of graphene

- October 2017MRS Communications 7(04):1-6



A Compressed Approach to the Theory of Crystal Growth. Thermodynamics, Kinetics and Transport

P. Rudolph

Crystal Technology Consulting
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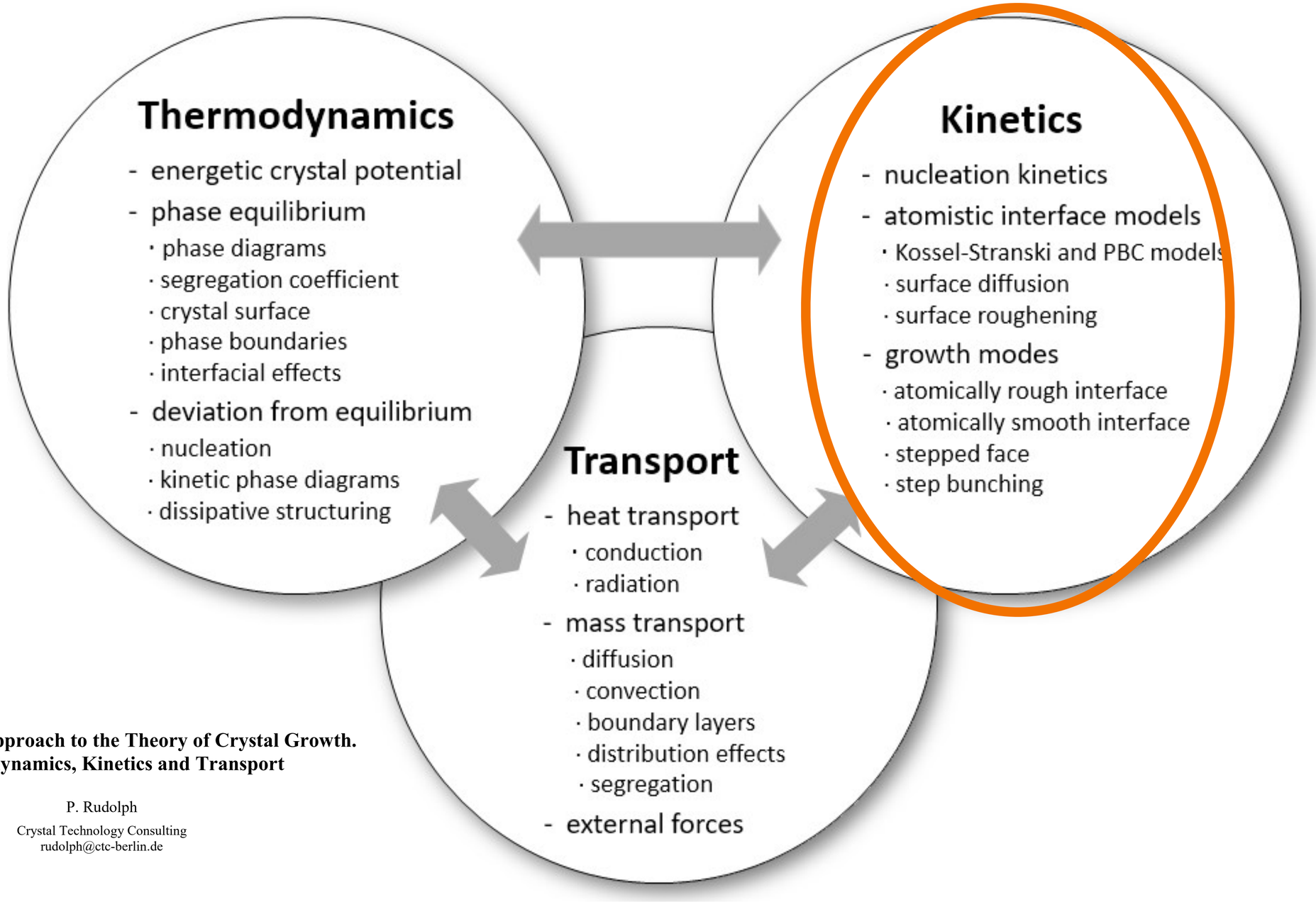

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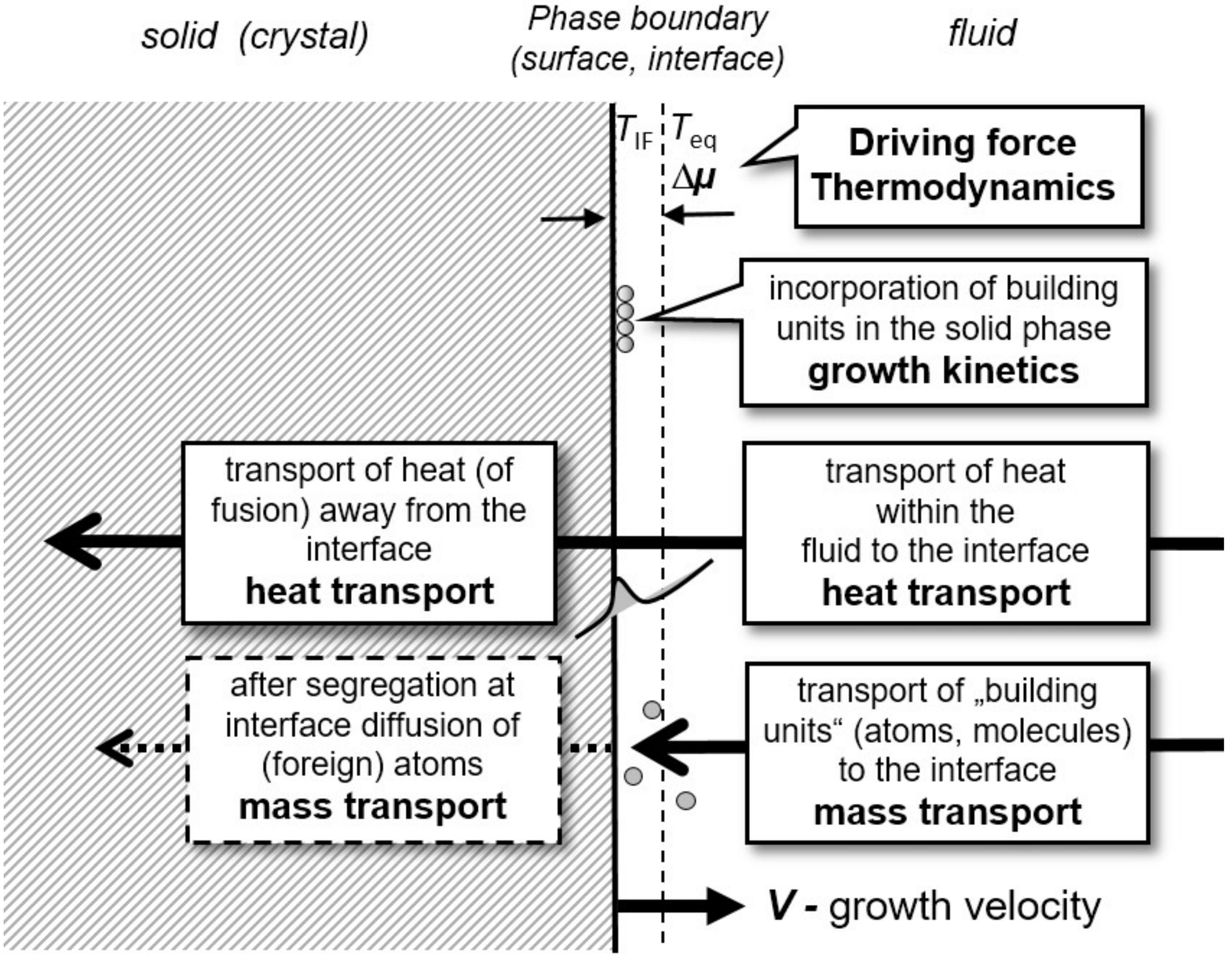
Interface processes during crystal growth



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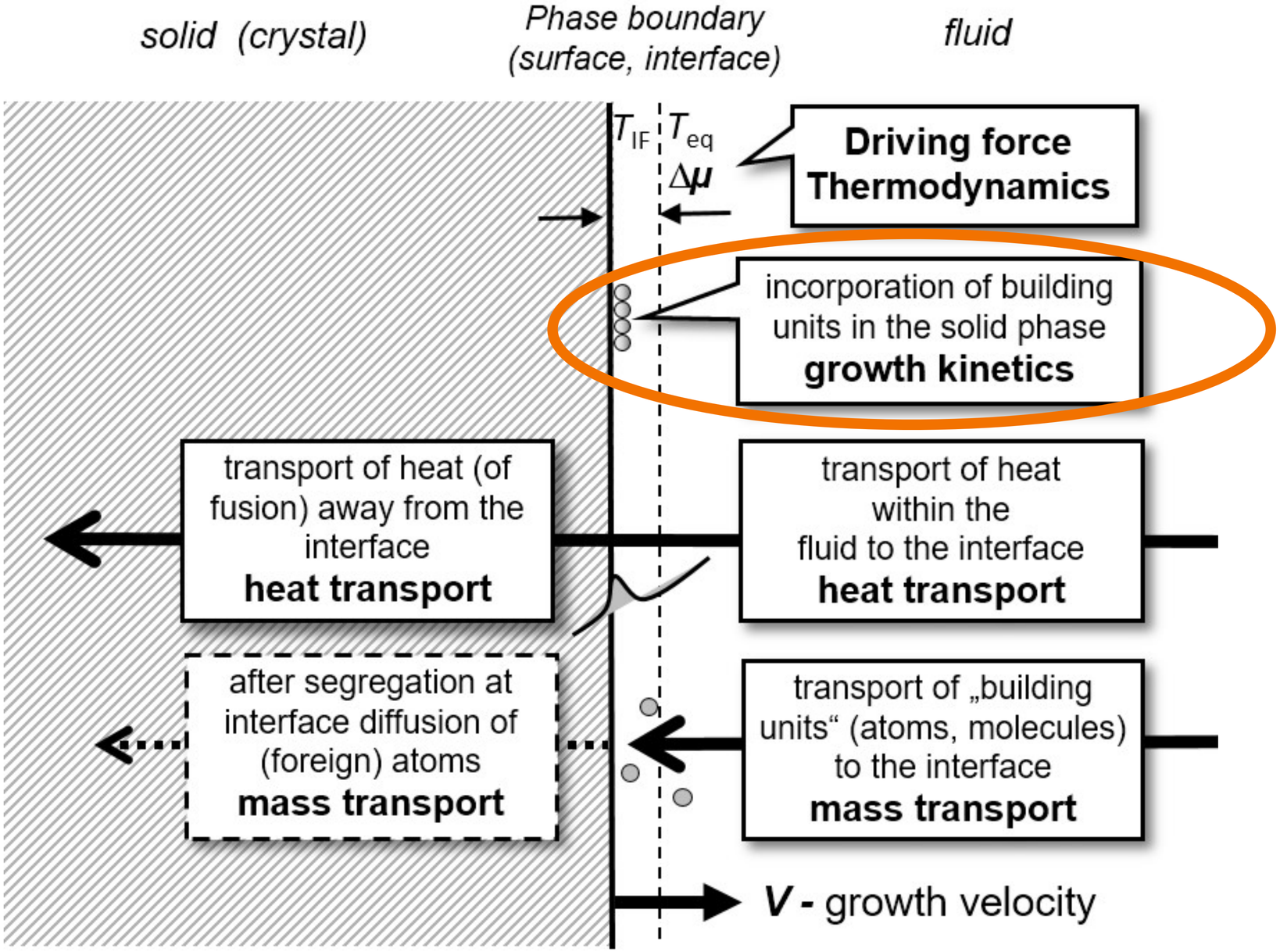

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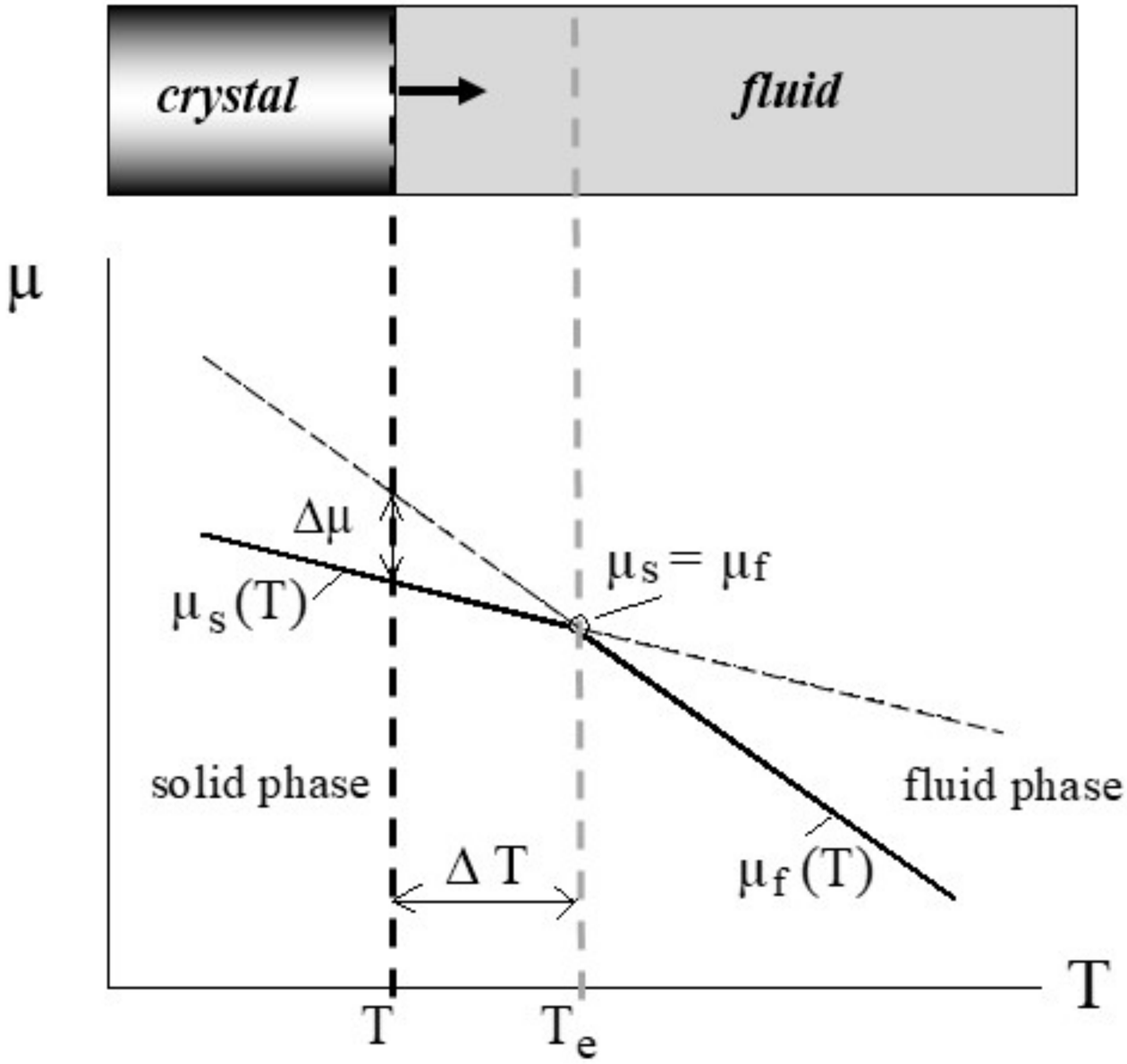
Driving force of crystal growth: supersaturation

$$G = G(T, P, N), \quad V = \left(\frac{\partial G}{\partial P}\right)_{T,N}$$

$$\mu(T, P) = \left(\frac{\partial G}{\partial N}\right)_{T,N}$$

$$\Delta\mu = k_B T \ln(1 + \Delta P / P_e)$$



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Epitaxy method	LPE	VPE	MOCVD	MBE
Relative super-saturation $\mathcal{S}$	~ 0.02 - 0.1	~ 0.5 - 2	~ 50	~ 10 - 100
Driving force $\Delta\mu$ J/mol (T = 1000 K)	~ 165 - 800	~ (3-9) x10^3	~ 3.3 x 10^4	~ (2-4) x10^4

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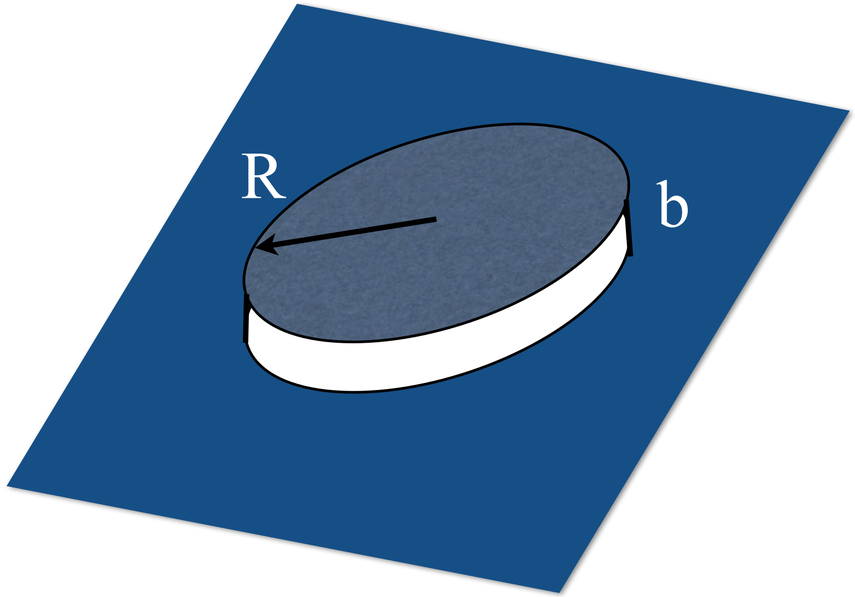
Classical nucleation theory

- Close to equilibrium (free energy, chemical potential)
- Computes the size (radius) of the critical cluster, nucleation barrier

Classical nucleation theory



$$\Delta G = 2\pi\gamma\, bR - \pi\Delta\mu\, bR^2$$

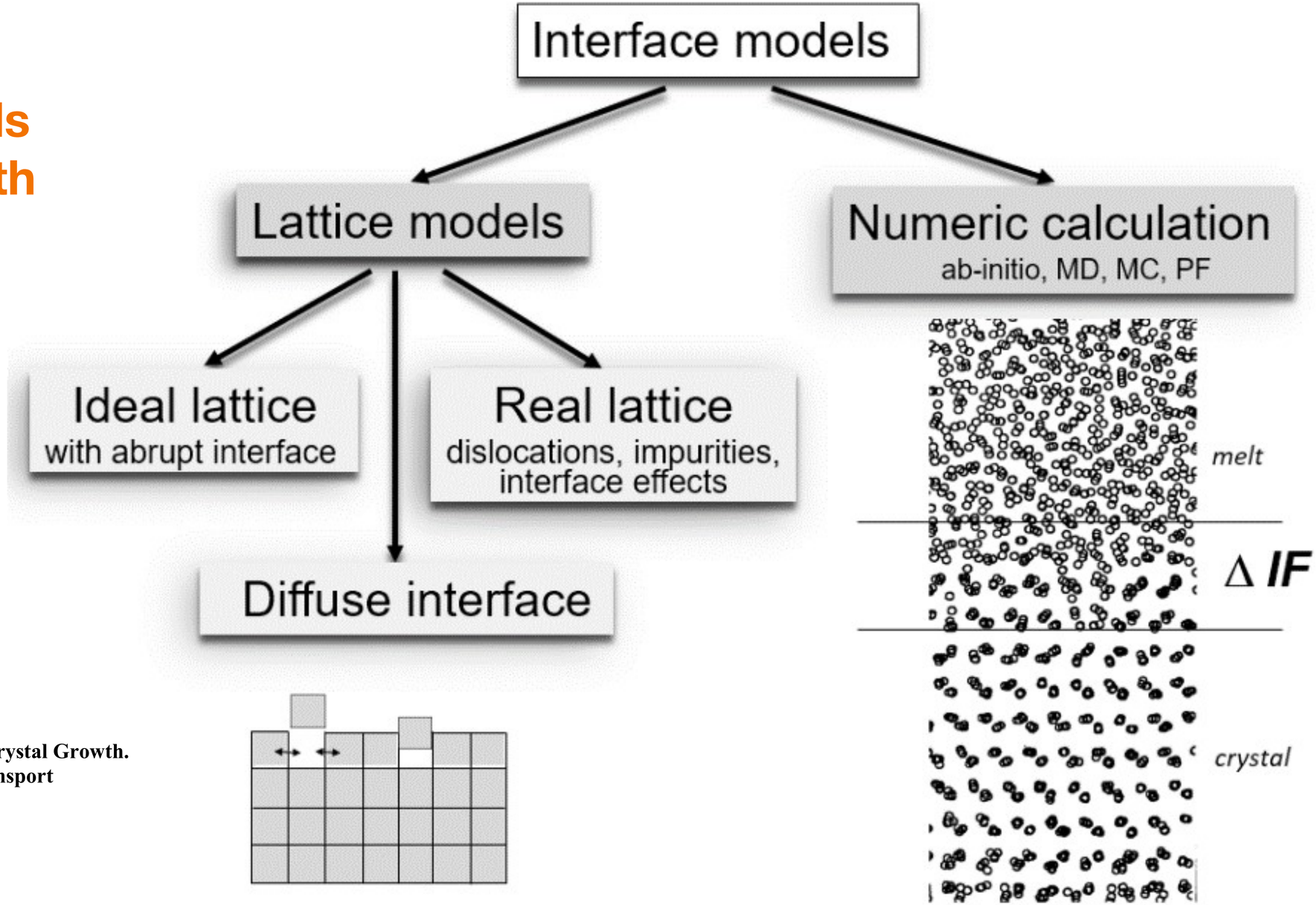
$$R_c = \frac{\gamma}{\Delta\mu}$$

Step free energy

$$\Delta G_c = \pi b \frac{\gamma^2}{\Delta\mu} = \pi b \frac{\gamma}{R_c}$$

R_c “critical nucleus size”

Numerical models and crystal growth



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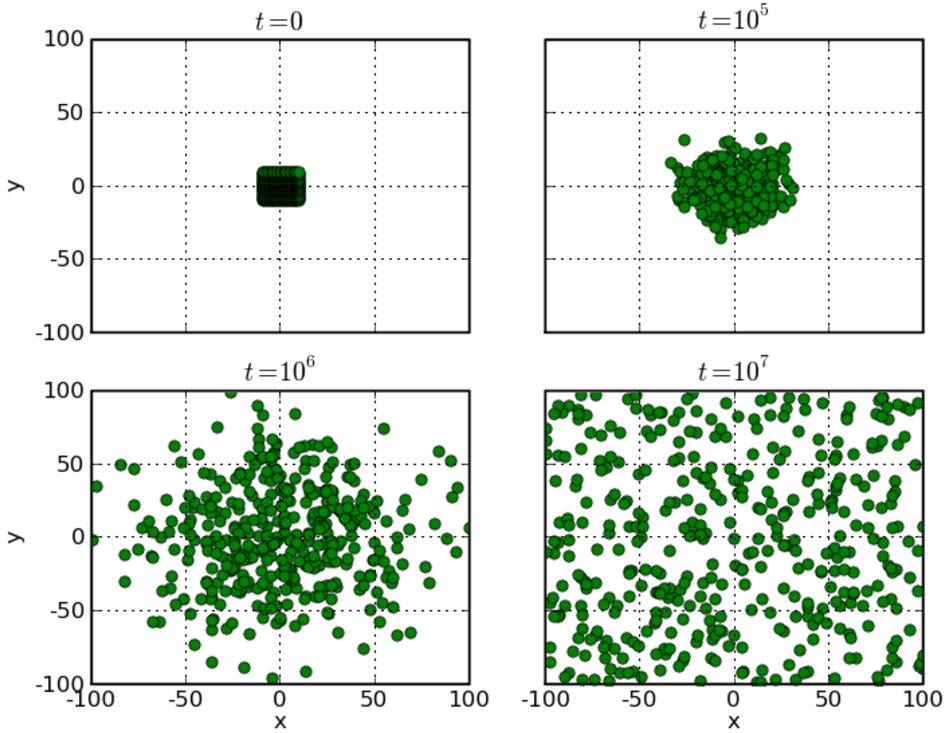
An example of numerical methods
Kinetic Monte Carlo (kMC)

Diffusion is a random walk!



Diffusion is a random walk!

(case $p_{\leftarrow} = p_{\rightarrow}$)

$$P(i,N) = \tfrac{1}{2}P(i+1,N-1) + \tfrac{1}{2}P(i-1,N-1)$$

Defining: $t = N\tau$, $x = i\ell$ we have:

$$P(x,t) = \tfrac{1}{2}P(x+l,t-\tau) + \tfrac{1}{2}P(x-l,t-\tau)$$

We rewrite this by subtracting $P(x,t-\tau)$ and dividing by τ

$$\frac{P(x,t) - P(x,t-\tau)}{\tau} = \frac{P(x+l,t-\tau) + P(x-l,t-\tau) - 2P(x,t-\tau)}{2\tau}$$

we get

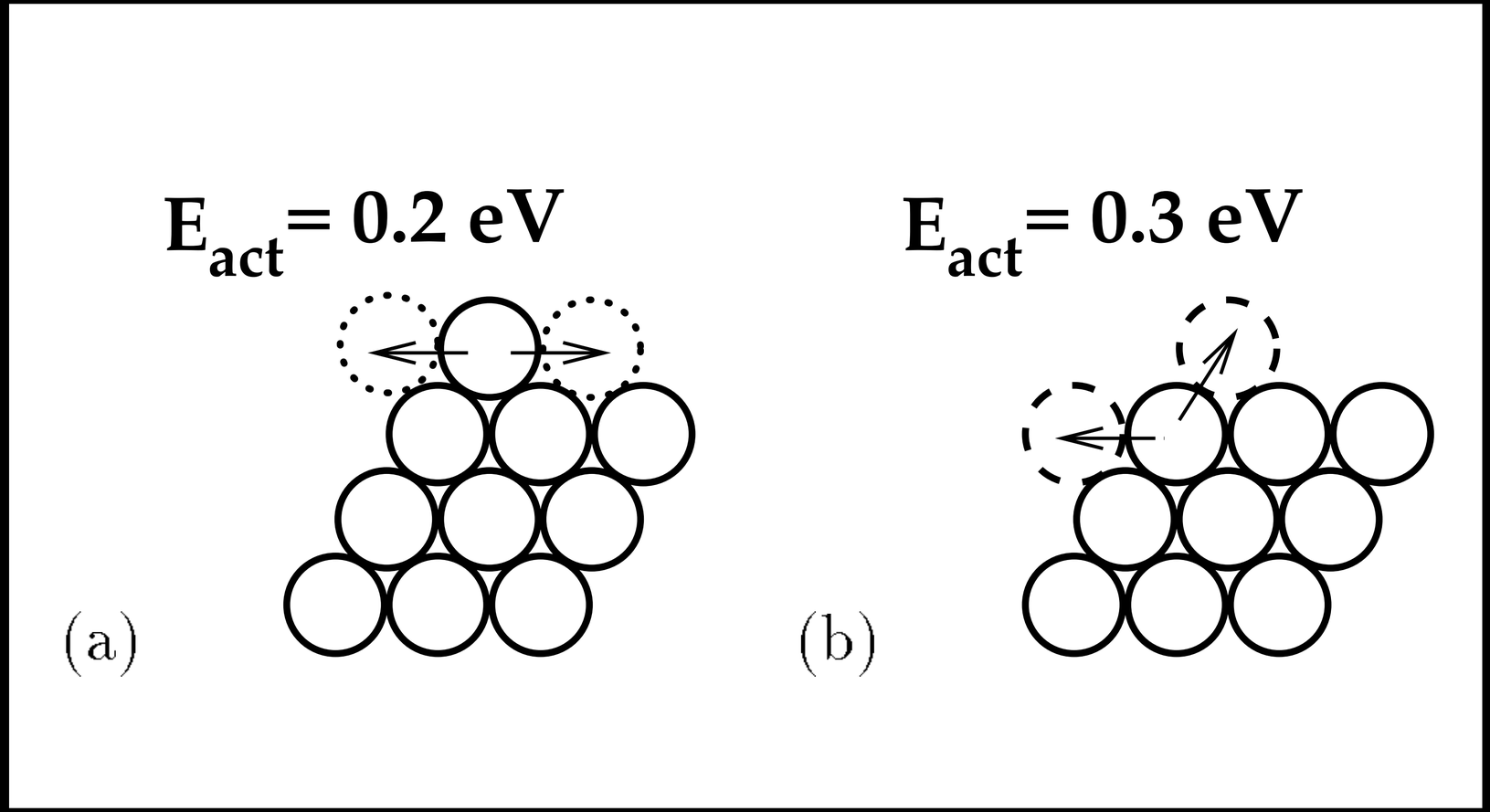
$$\frac{\partial P(x,t)}{\partial t} \approx \frac{l^2}{2\tau}\frac{\partial^2 P(x,t)}{\partial x^2}$$

In the limit $\tau \to 0, l \to 0$ but where the ratio l^2/τ is finite, this becomes an exact relation.

An example of numerical methods
Kinetic Monte Carlo (kMC)

$$p_i = \nu_0 e^{\frac{-iE}{k_b T}}$$

$E = 0.1$ eV



My own The Big Bang Theory moment

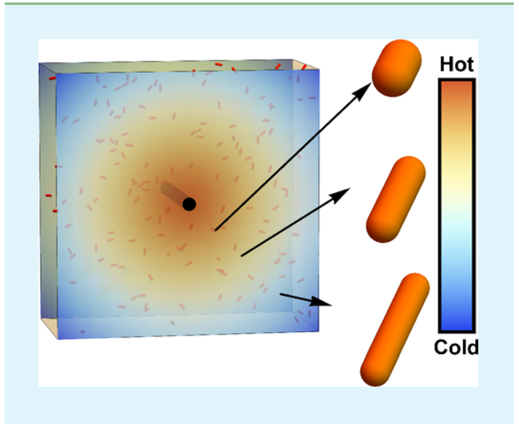
ACS APPLIED MATERIALS & INTERFACES

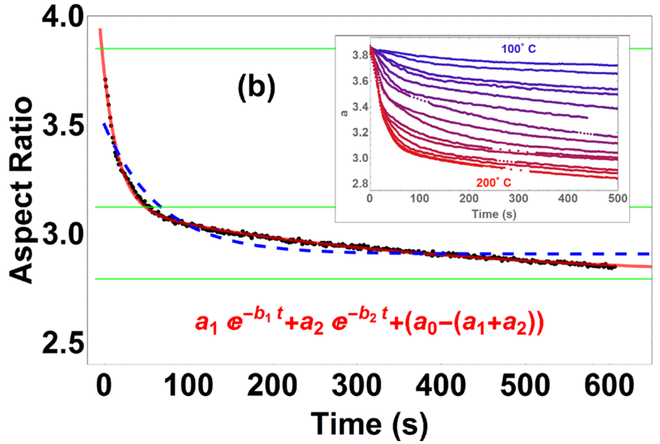
Research Article

www.acsami.org

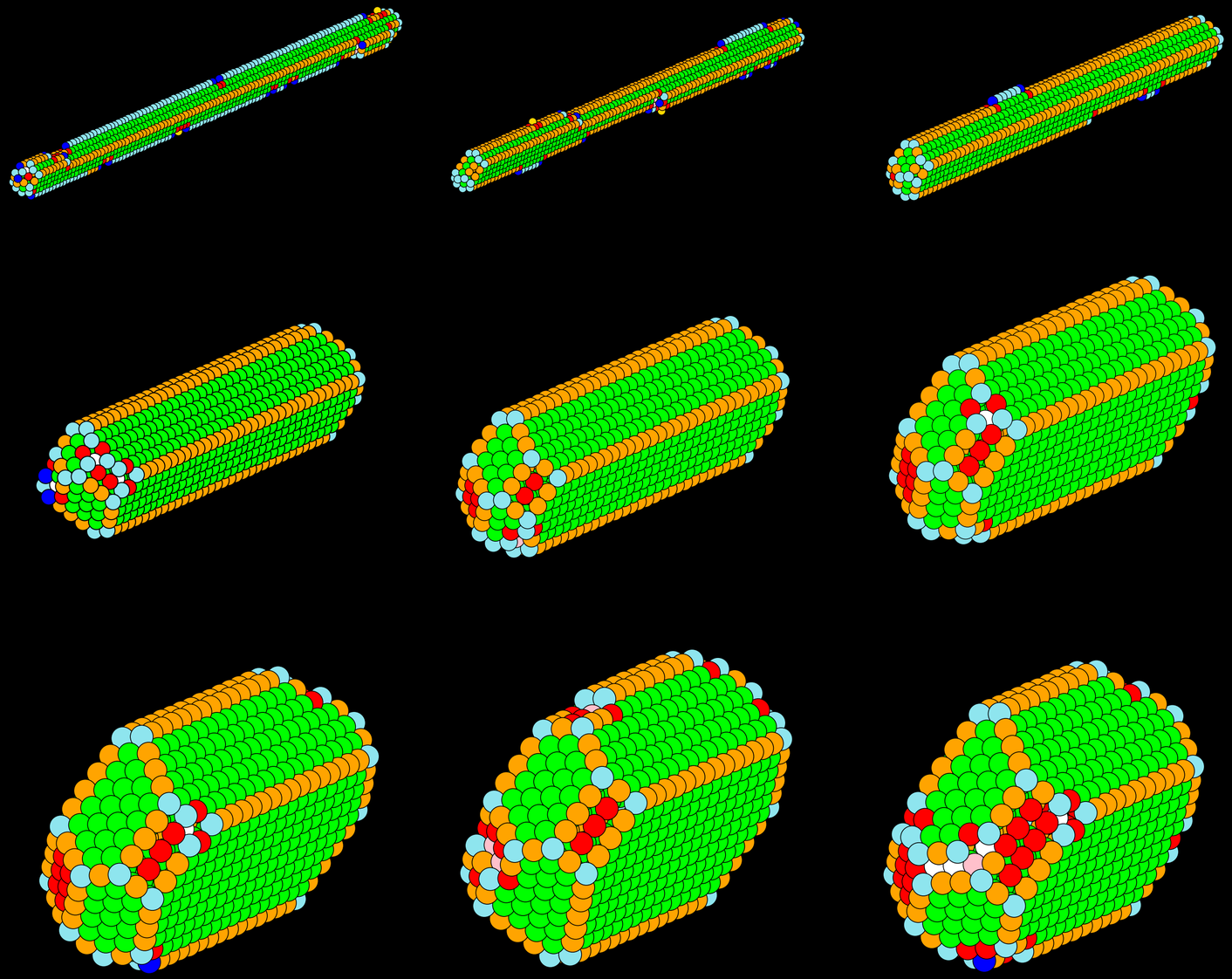
High-Resolution Mapping of Thermal History in Polymer Nanocomposites: Gold Nanorods as Microscale Temperature Sensors

W. Joshua Kennedy,[†,‡] Keith A. Slinker,[†,‡] Brent L. Volk,[‡] Hilmar Koerner,[‡] Trenton J. Godar,[§,‡] Gregory J. Ehlert,[‡] and Jeffery W. Baur*[,‡]

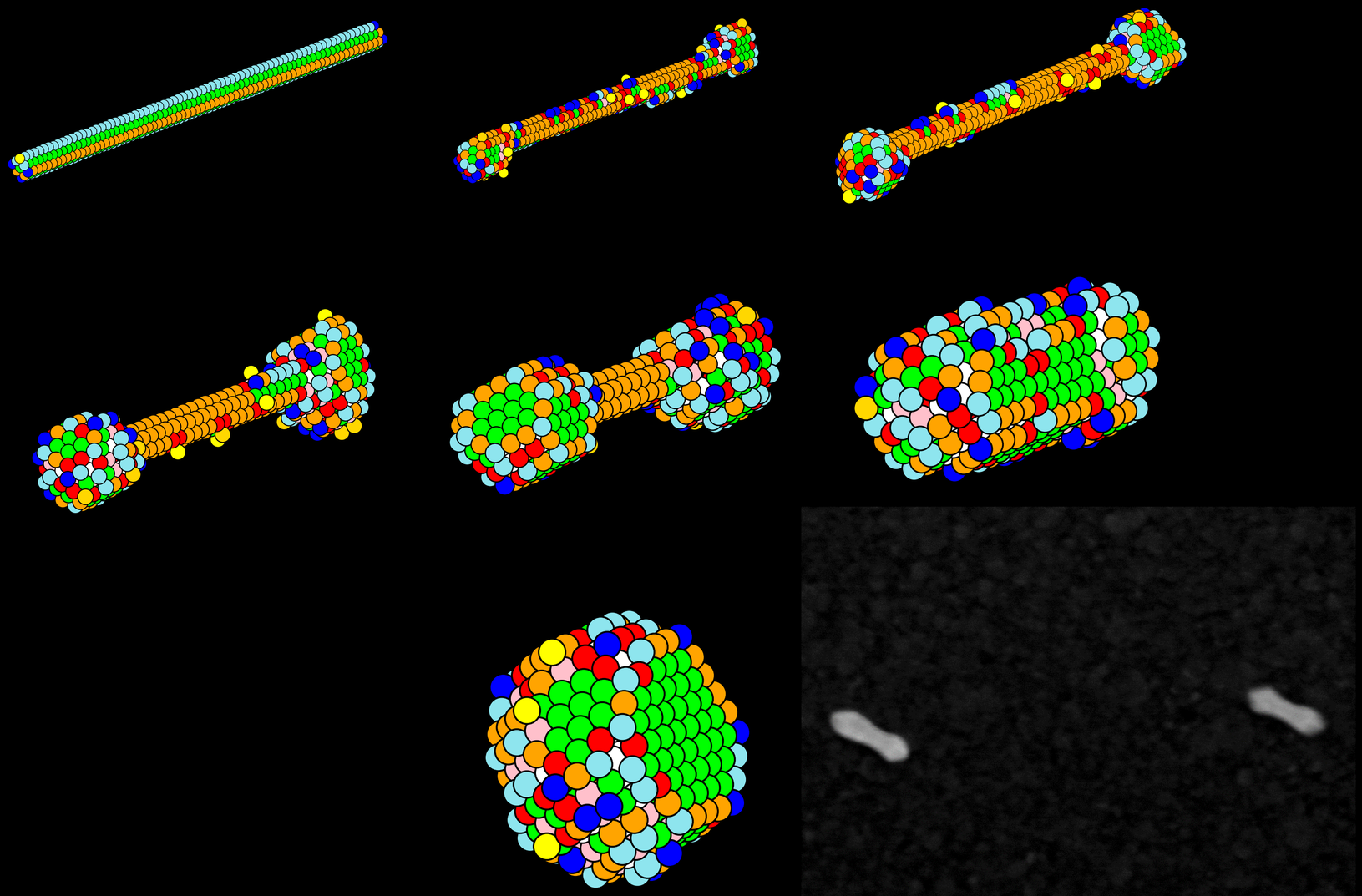


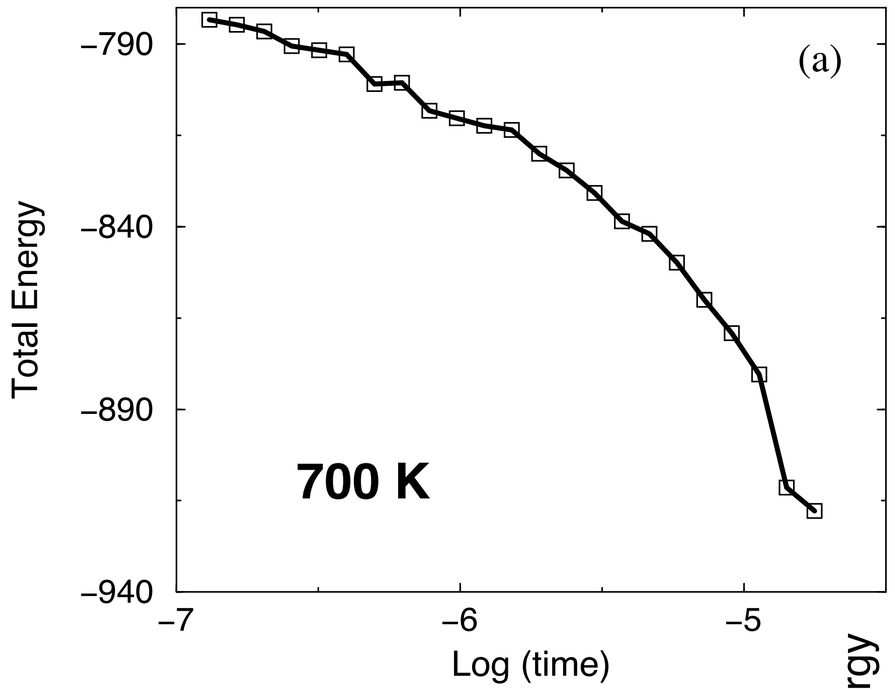


$N = 1728$, $T = 300$K time evolution

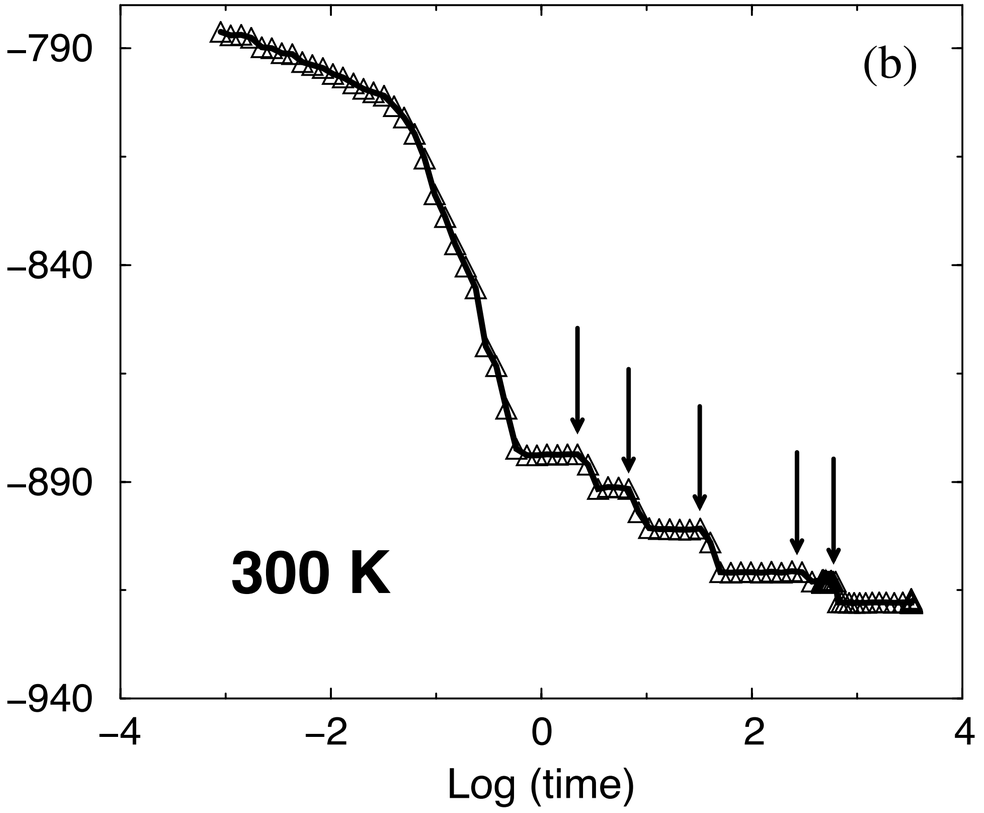


$N = 675$, $T = 700$K time evolution

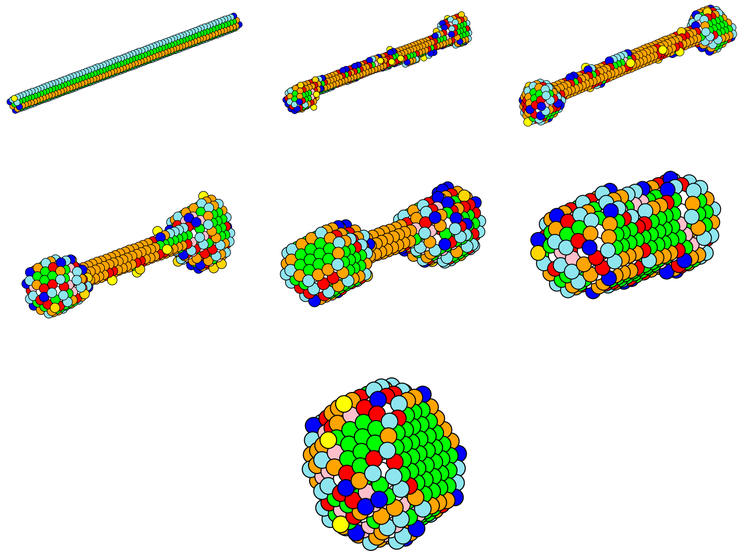


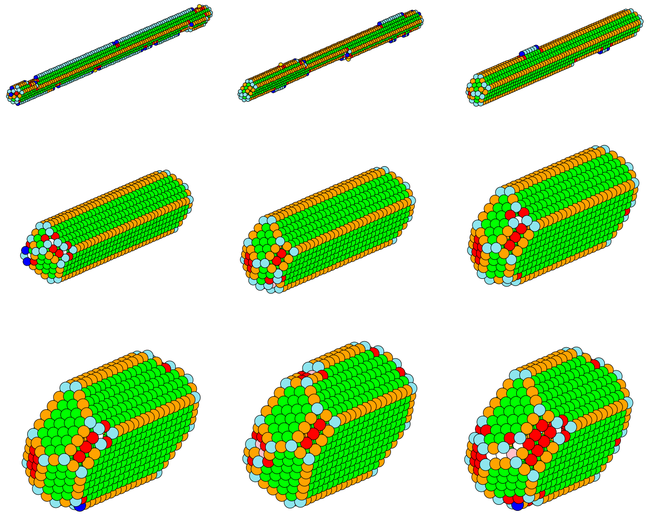


Total energy



Equilibration time: time needed to attain an aspect ratio of 1.2

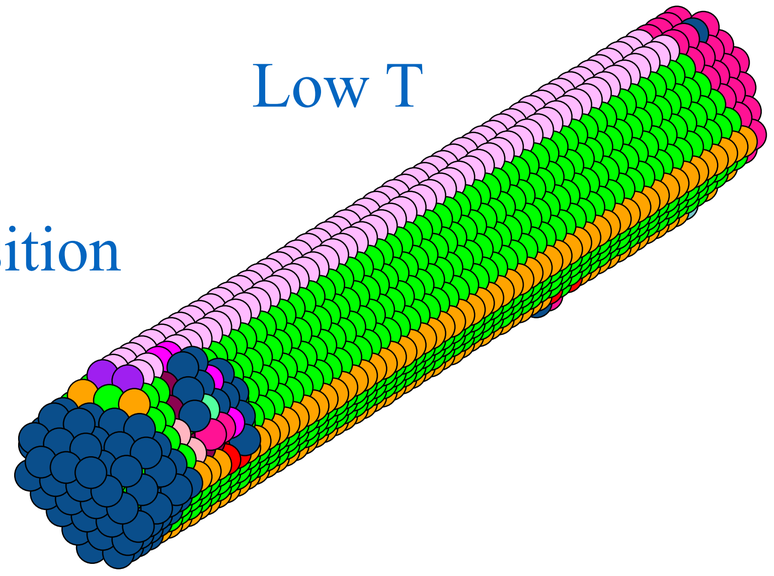




High T

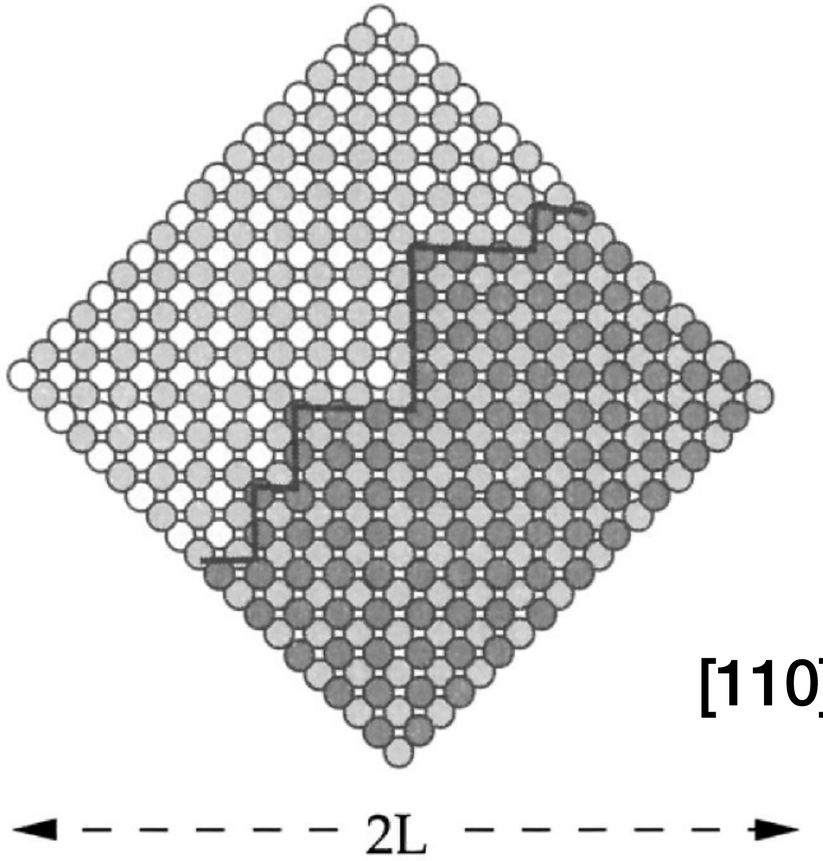
Low T

Roughening transition



The Roughening Transition

Step Free Energy: work needed to create a step, per bond

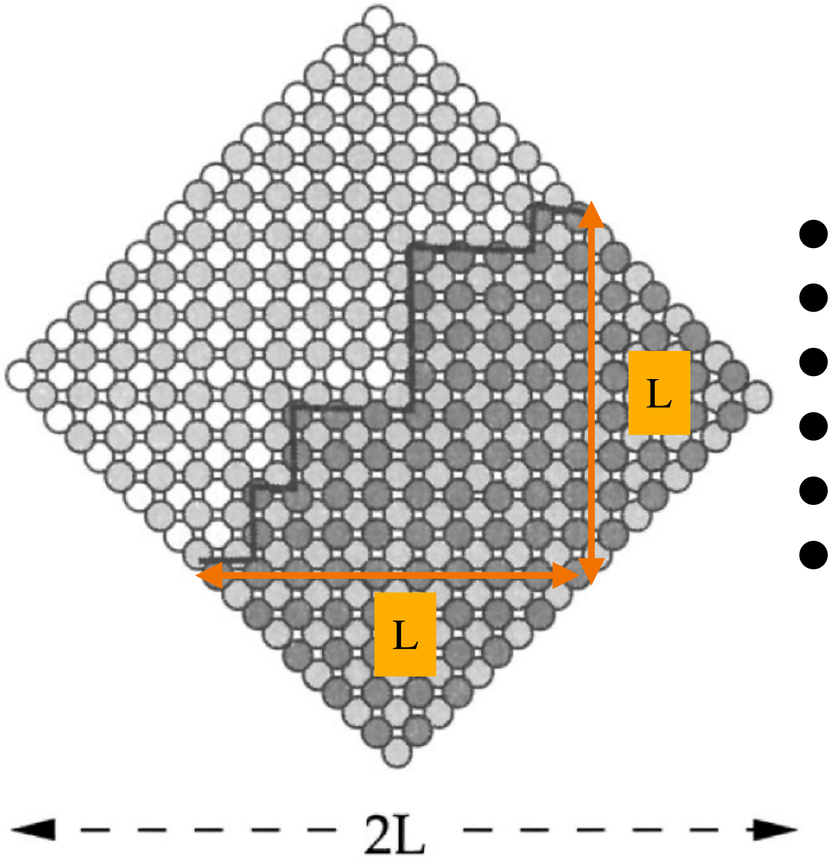


$$\Delta G^* = \pi h \gamma^2 / \Delta\mu$$

[110] step on a (100) surface

The Roughening Transition

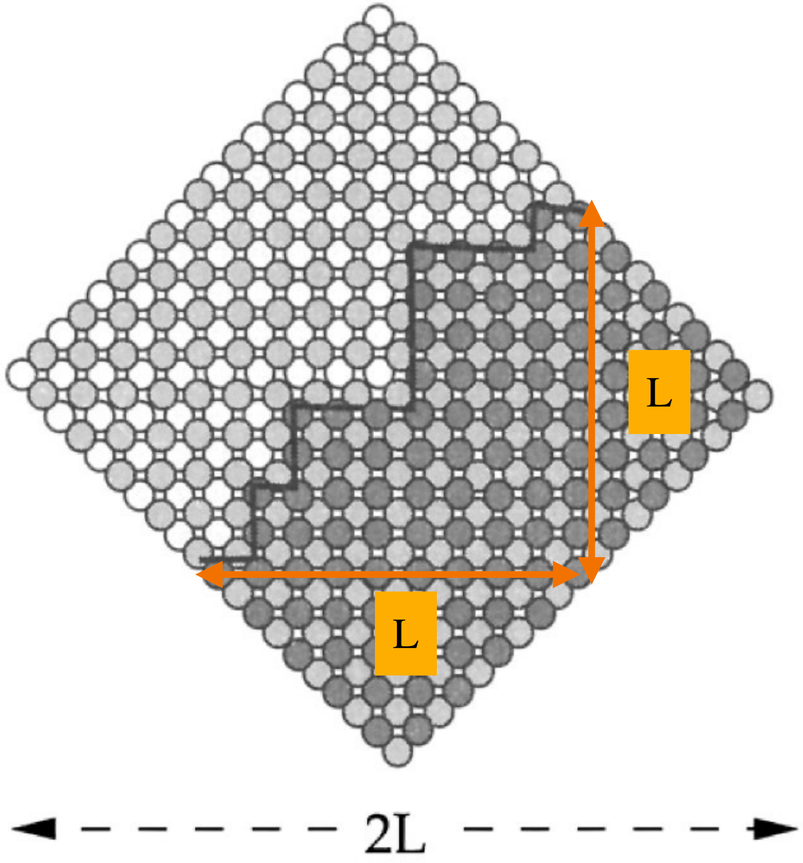
Step Free Energy: work needed to create a step, per bond



- Step: random walk from left to right (fixed ends)
- Number of steps = number of bonds = $2\mathrm{L}$
- Bond energy = W_1
- Total energy = $2\mathrm{L}W_1$
- Number of configurations = $2^{2\mathrm{L}}$
- Entropy = $2\mathrm{L}\, k_B \ln 2$

The Roughening Transition

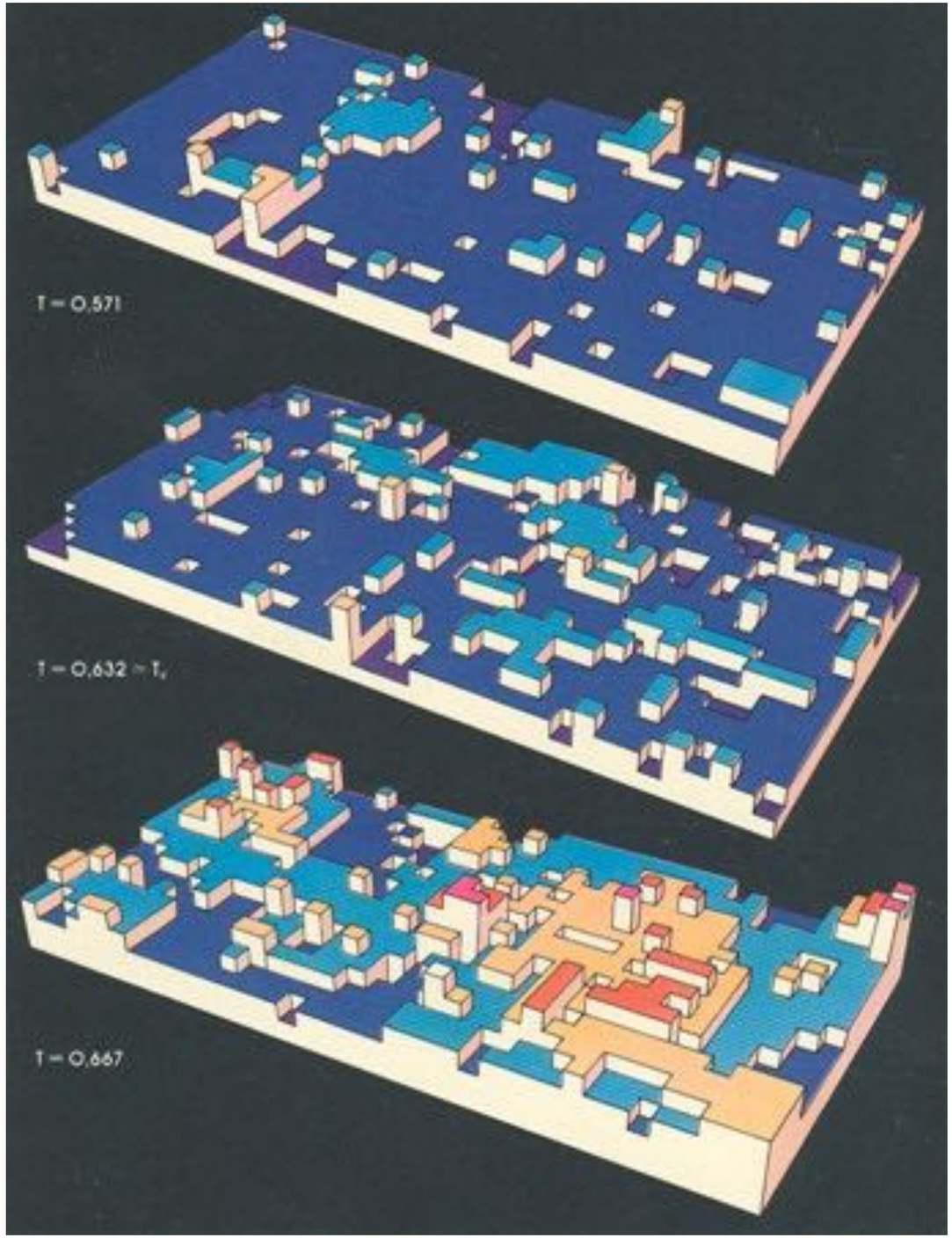
Step Free Energy: work needed to create a step, per bond



$$\gamma = e - Ts$$

$$\gamma = W_1 - k_B T \ln 2$$

$$\gamma = 0 \rightarrow T_R = \frac{W_1}{k_B \ln 2}$$



Surfaces: smooth and rough

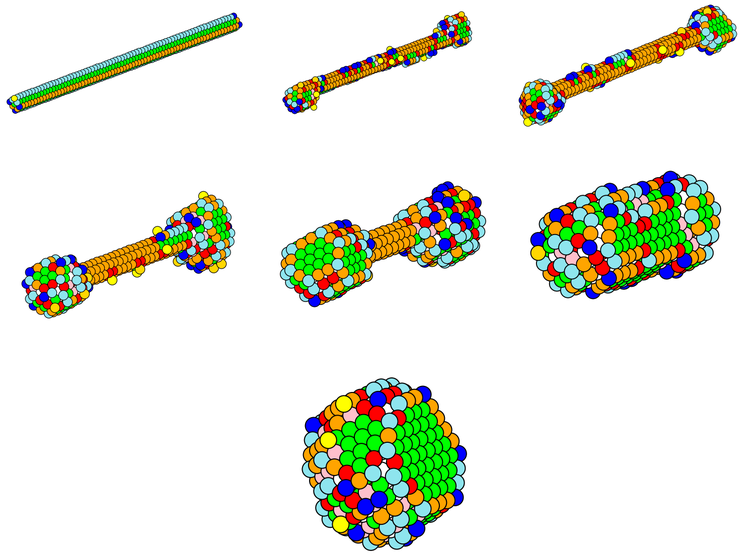
$$\gamma = 0 \rightarrow T_R = \frac{W_1}{k_B \ln 2}$$

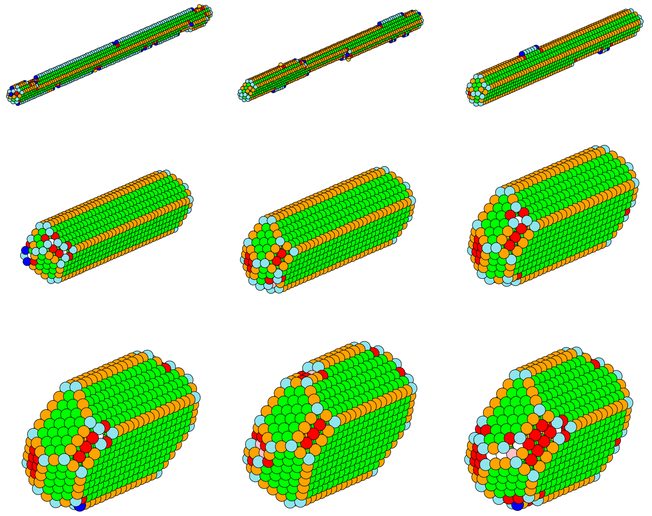
$$T < T_R$$

$$\langle [z(\vec{r} + \vec{R}) - z(\vec{r})]^2 \rangle \sim \text{const}\,.$$

$$T > T_R$$

$$\langle [z(\vec{r} + \vec{R}) - z(\vec{r})]^2 \rangle \sim (4\pi k_B T/\tilde{\sigma}) \ln R$$





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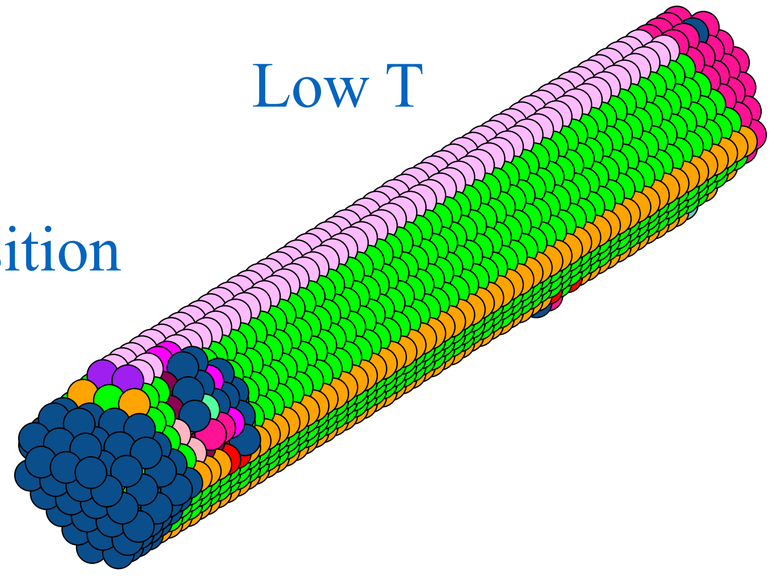
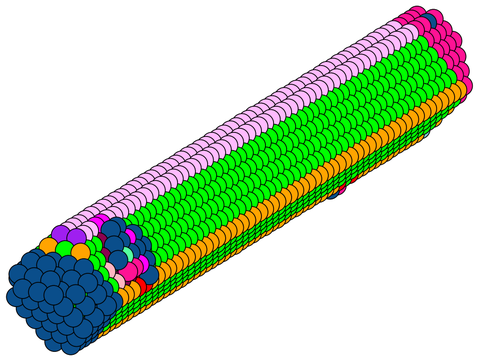
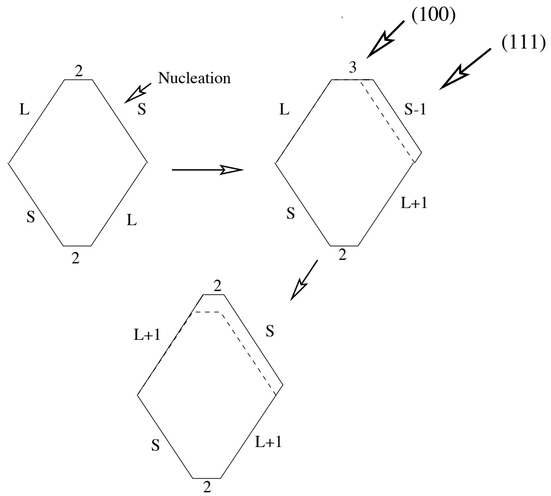
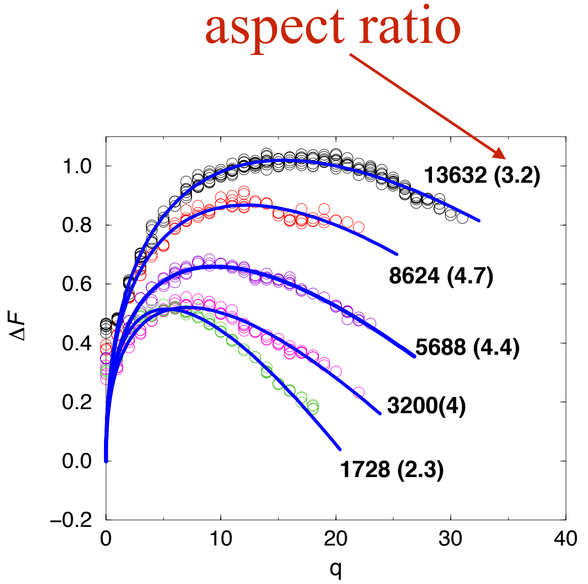


Classical nucleation theory



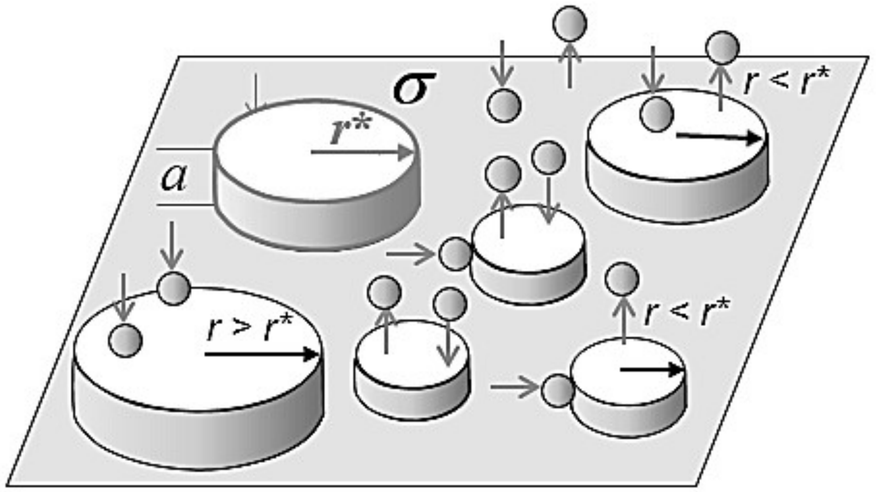


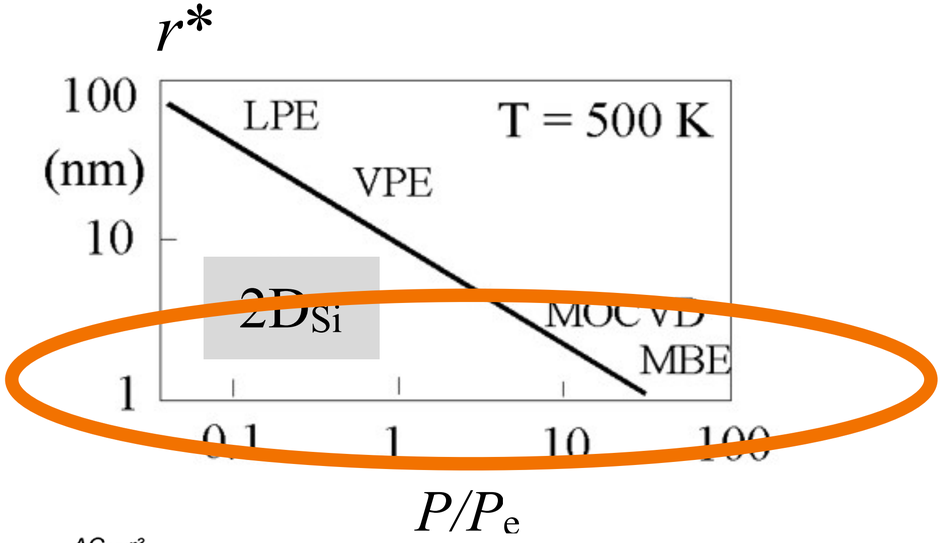


$$\Delta G = 2\pi\,\gamma\,bR - \pi\,\Delta\mu\,bR^2$$

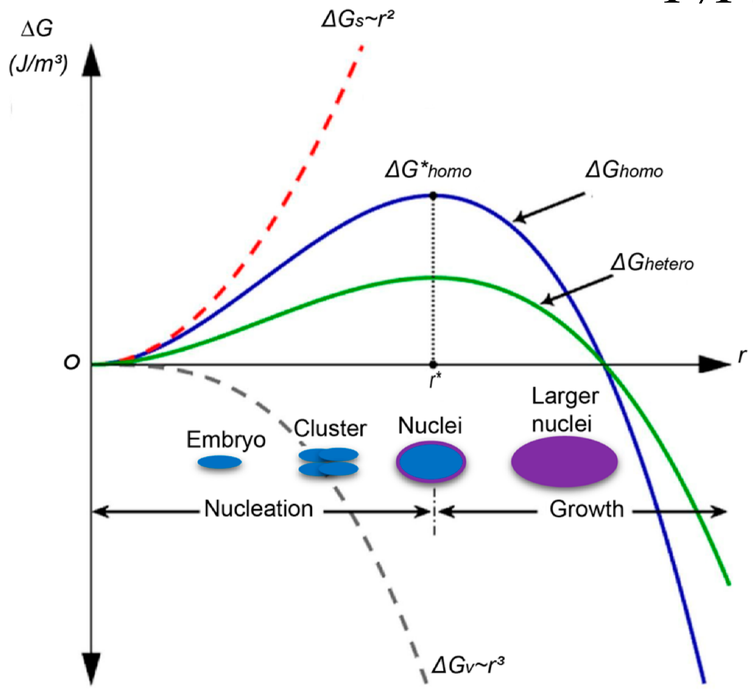
$$\Delta\mu = \gamma/R_c$$

Nucleation and critical nucleus





$$\Delta\mu = k_B T \ln(1 + \Delta P/P_e)$$



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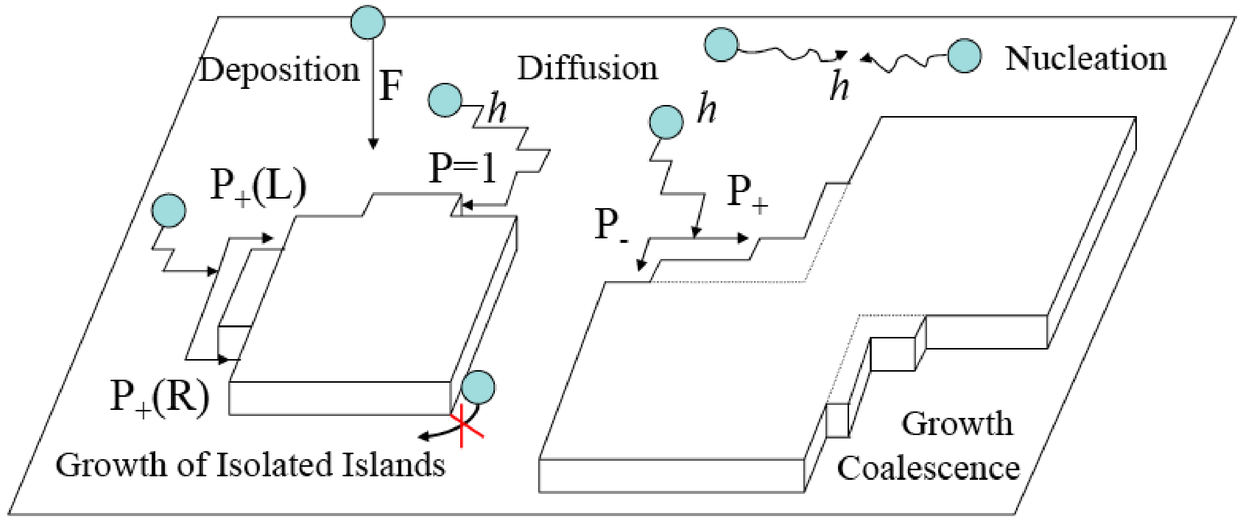
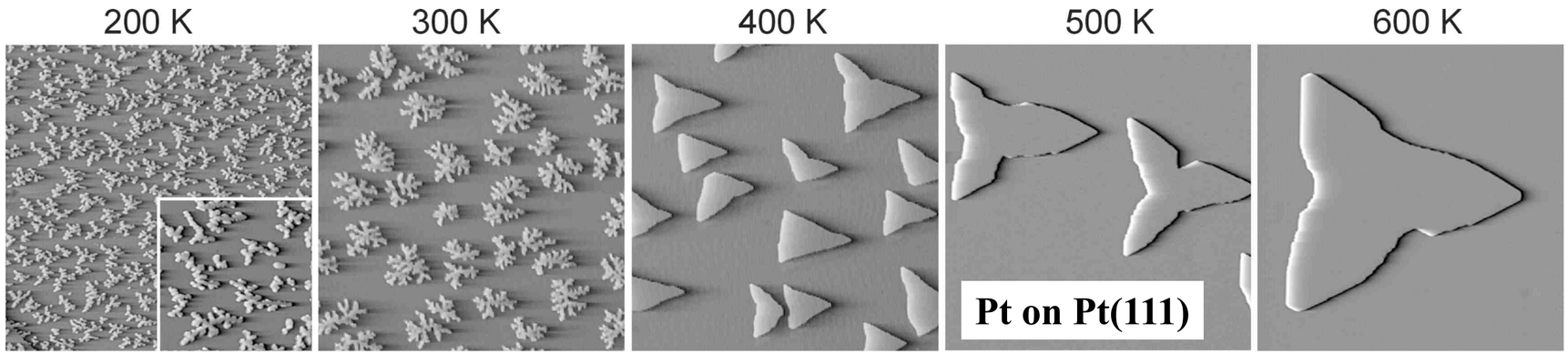
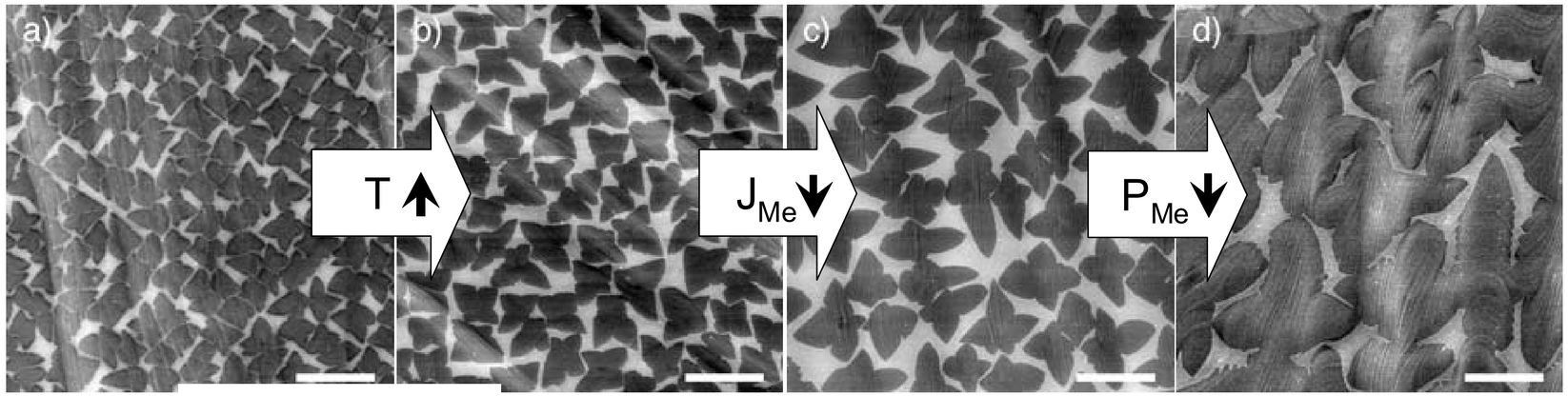
Deposition, diffusion, nucleation and aggregation on substrates

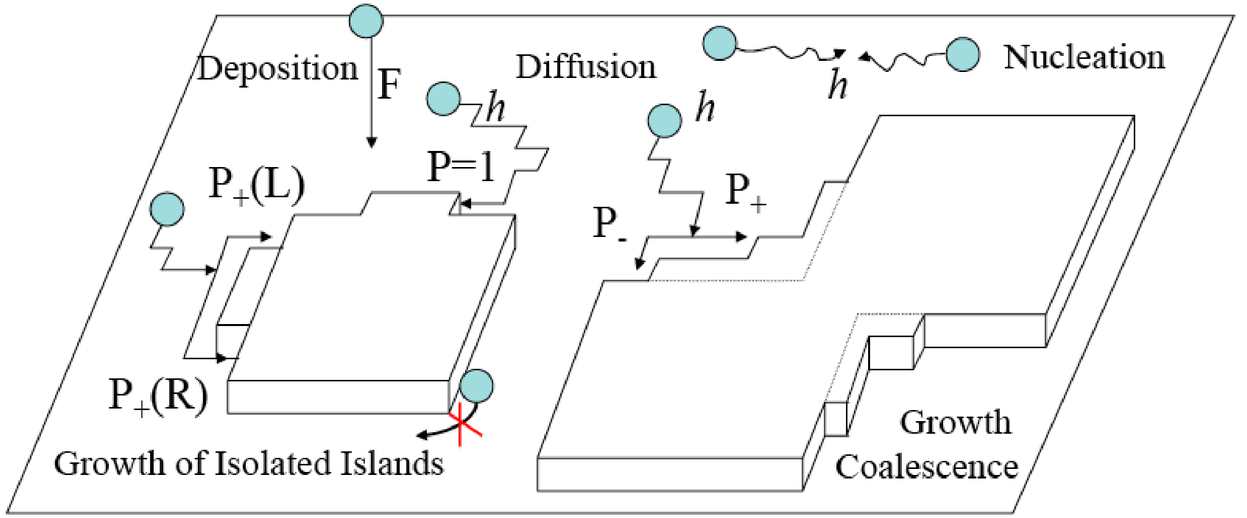


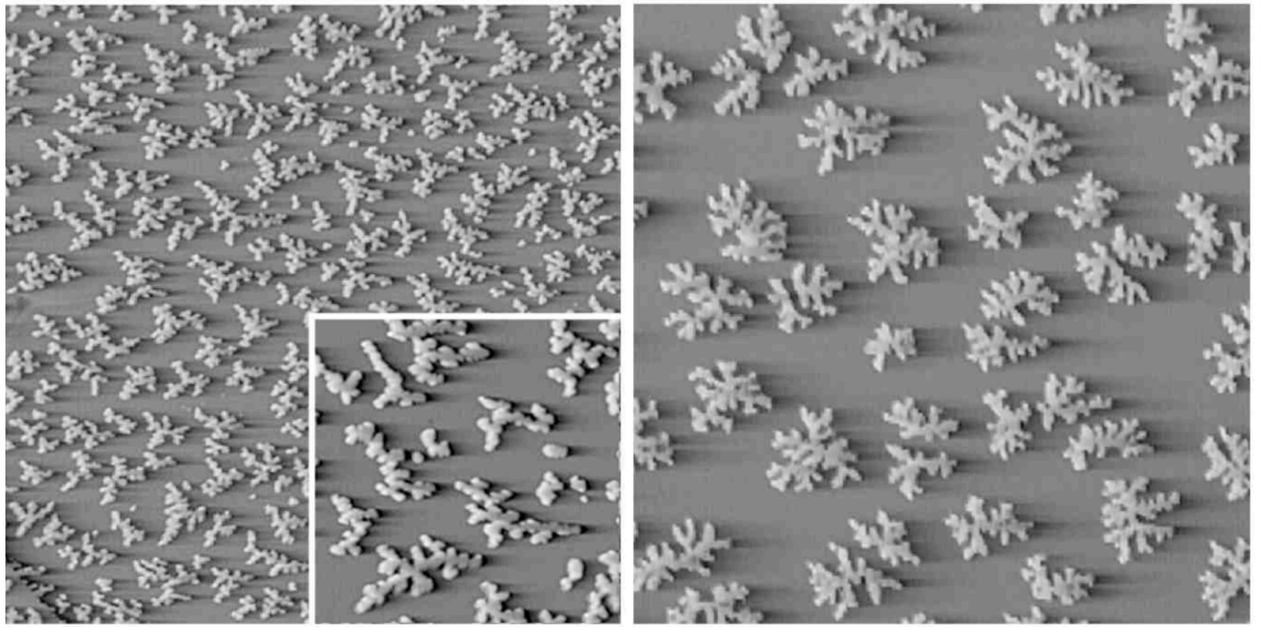
Deposition, diffusion, and aggregation on substrates



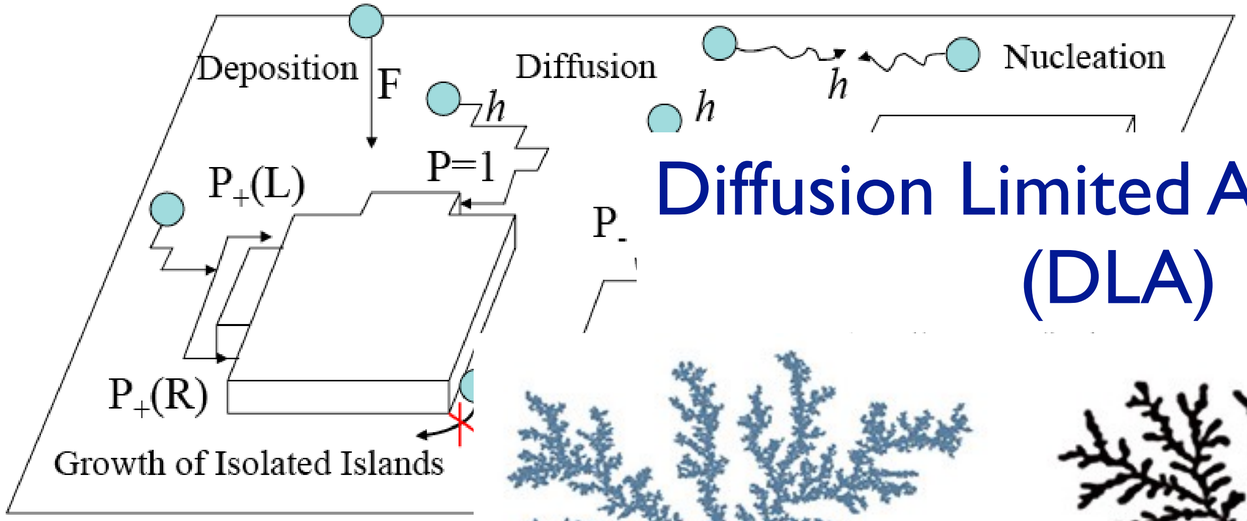


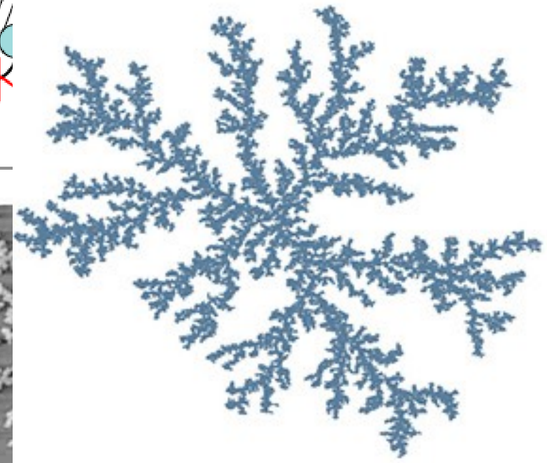
Graphene on Cu

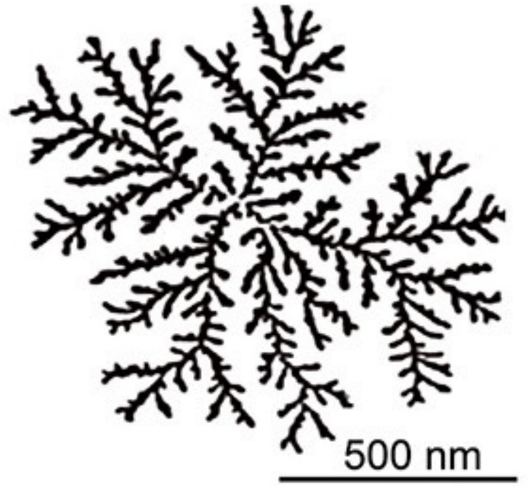

Deposition
F
Diffusion
Nucleation
h
h
h
P=1
P+(L)
P+(R)
P-
P+
Growth of Isolated Islands
Growth
Coalescence

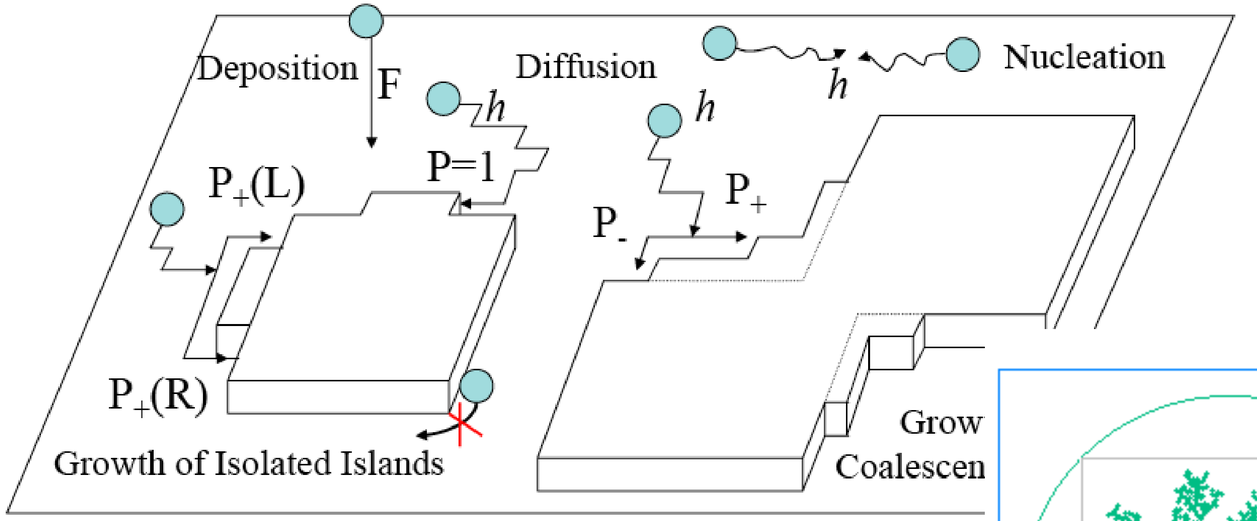


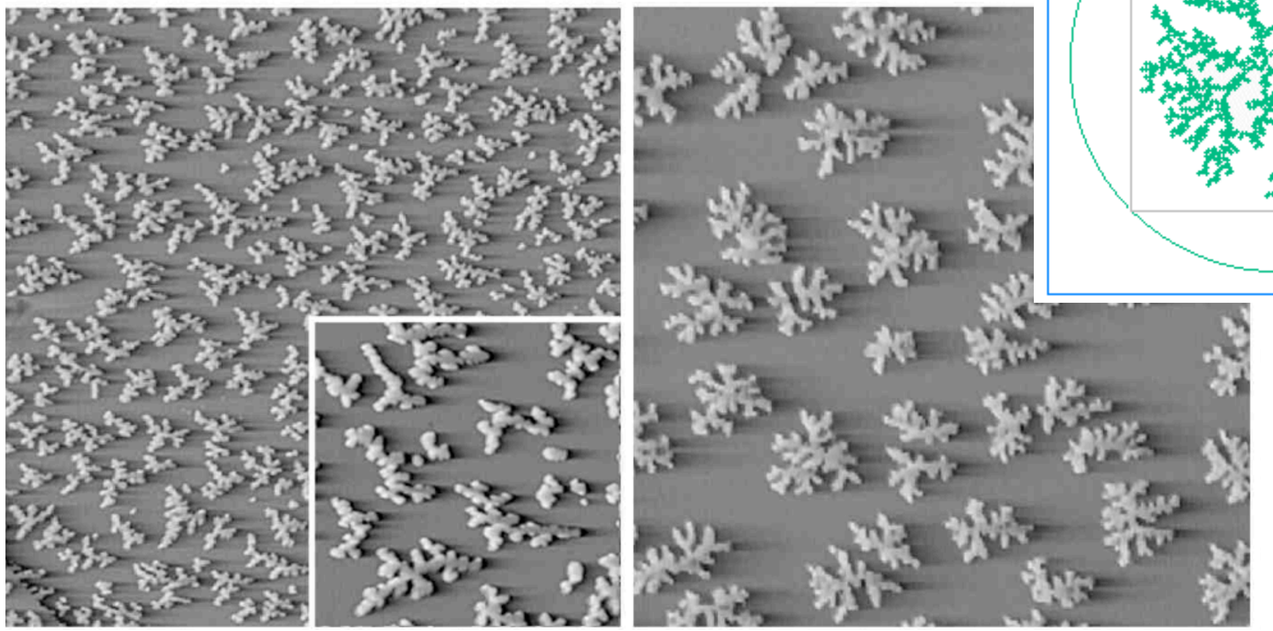
Diffusion Limited Aggregation (DLA)

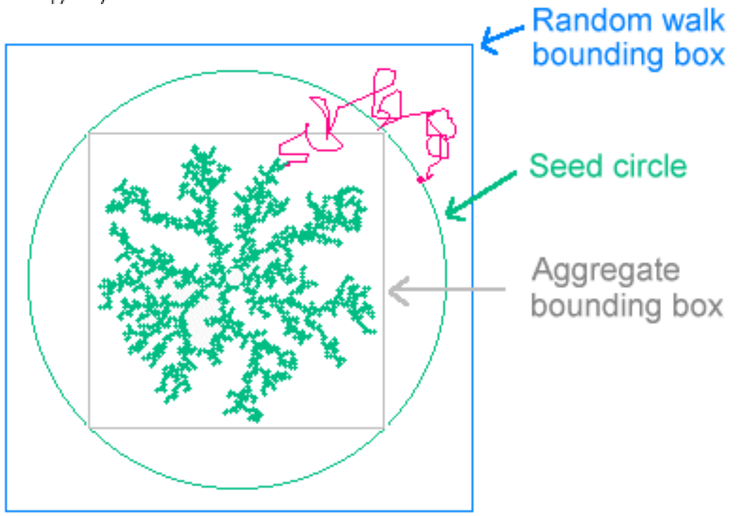




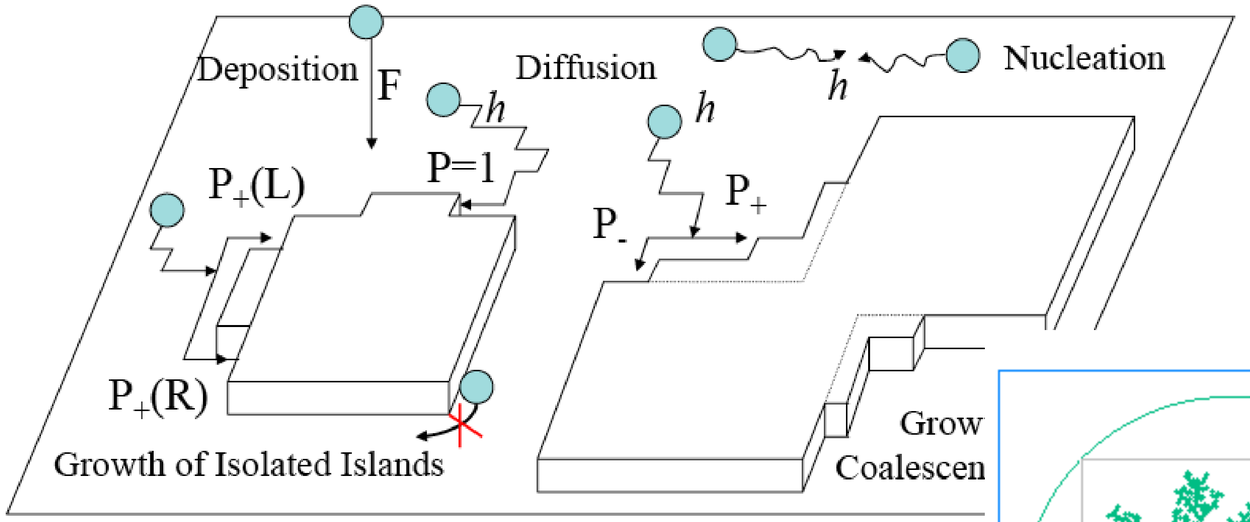


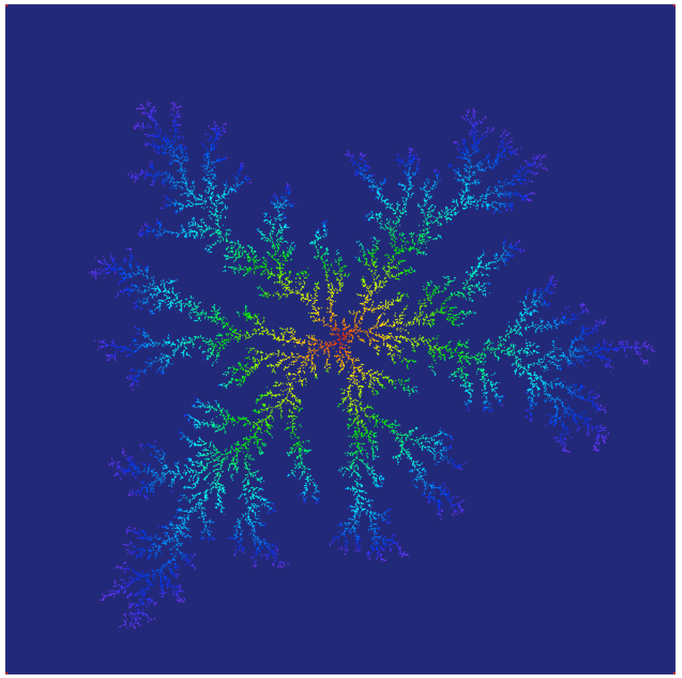


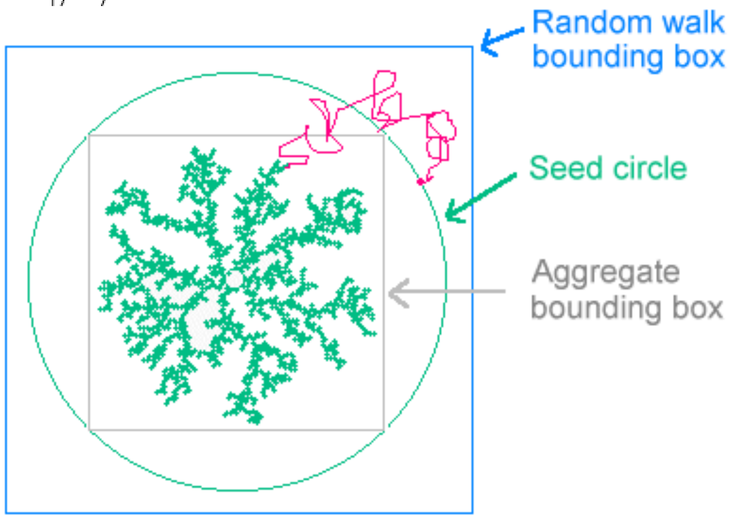




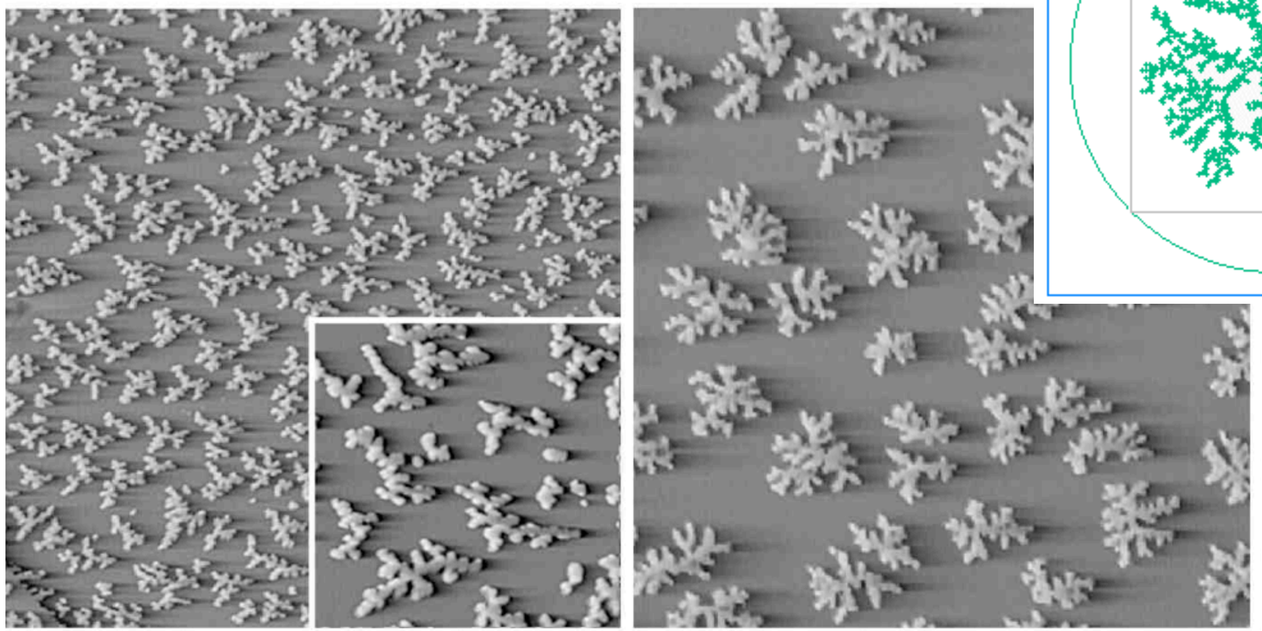
"Hit and stick"

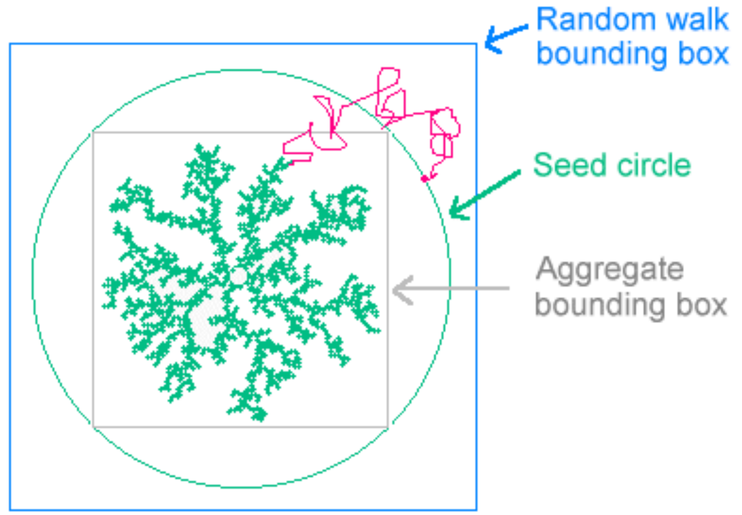

Deposition
F
Diffusion
h
h
h
Nucleation
P=1
P+(L)
P-
P+
P+(R)
Grow
Coalescen
Growth of Isolated Islands




Random walk
bounding box
Seed circle
Aggregate
bounding box

$R_c = 1$!! "critical nucleus" is a monomer!

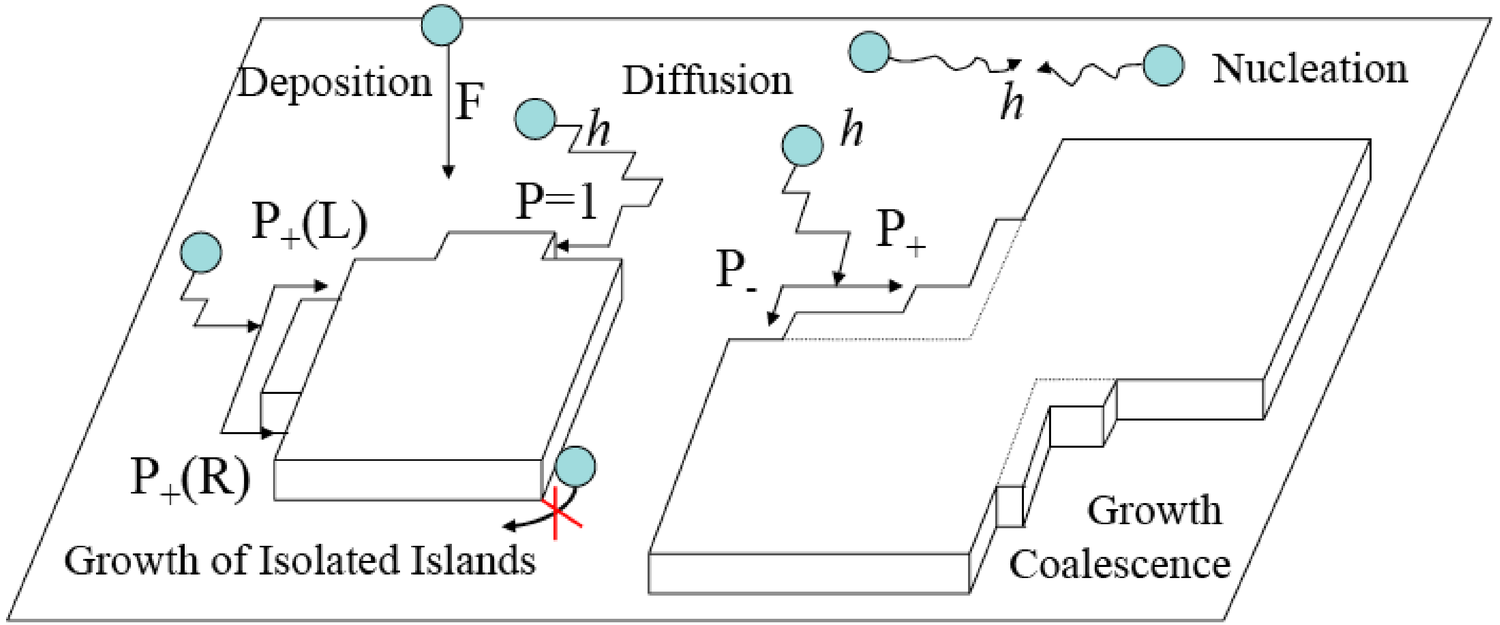




"Hit and stick"

Task: building a kinetic theory of nucleation

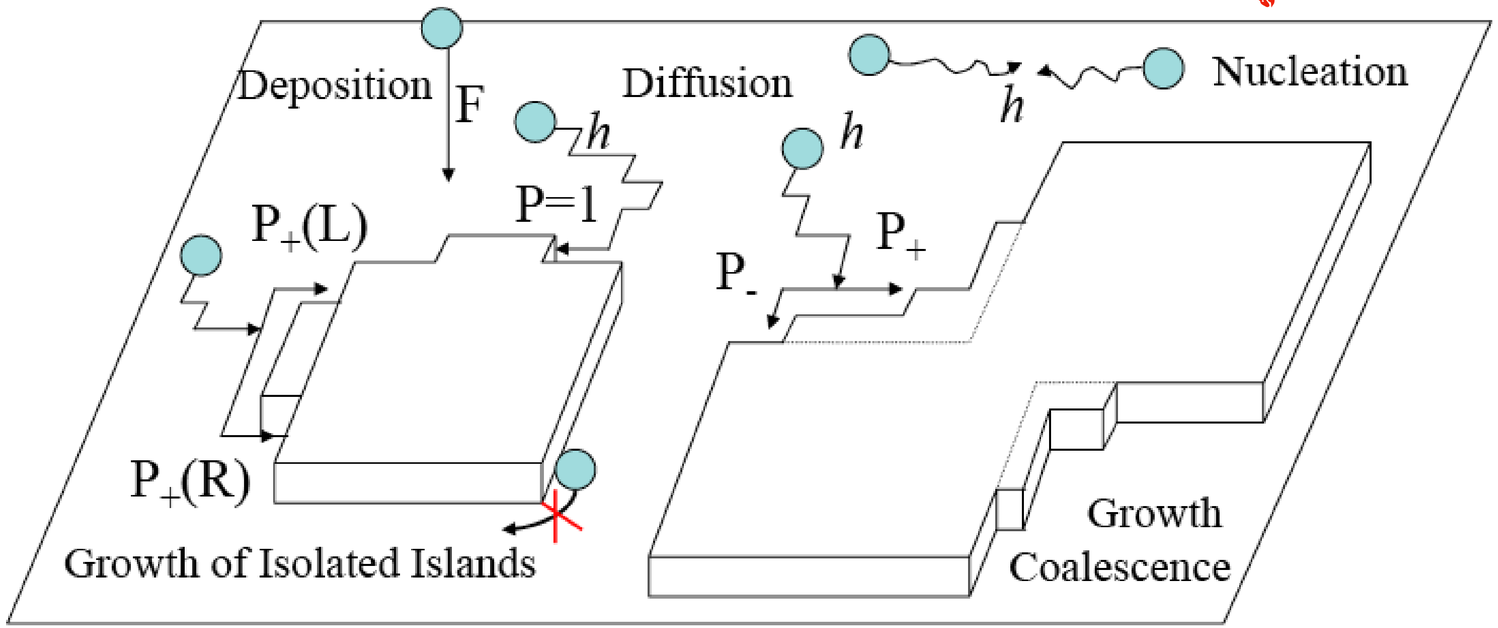
Nucleation Kinetics
Critical Nucleus Size



Task: building a kinetic theory of nucleation

Mean field

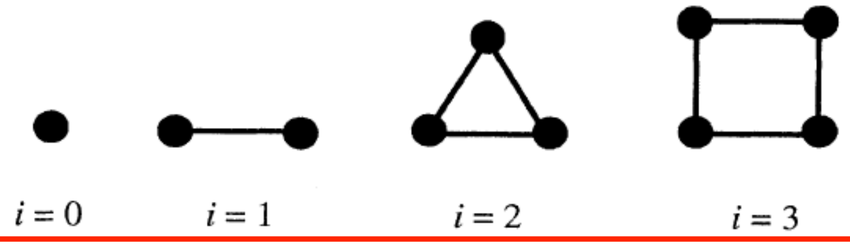
Nucleation Kinetics
Critical Nucleus Size



Kinetic theory of nucleation

- Rate equations
- Clusters with s monomers have density N_s
- Diffusing monomers have density n
- ***Assume*** critical nucleus is cluster with size $s = \boldsymbol{i}$

***i*+1 atoms: smallest stable island,**
i* atoms: *critical nucleus



Parameters: deposition rate F; diffusion constant D; Critical Nucleus Size i

$$\dot{n} = F - 2Dn^2 - DnN$$

$$\dot{n} = 0, \qquad n \ll N$$

$$n = \frac{F}{DN}$$

$$\begin{aligned}
\dot{N}_s &= \sigma_{s-1} n N_{s-1} - \sigma_s n N_s + \frac{1}{\tau_{s+1}} N_{s+1} - \frac{1}{\tau_s} N_s \qquad s < i \\
\dot{N}_i &= \sigma_{i-1} n N_{i-1} - \sigma_i n N_i - \frac{1}{\tau_i} N_i \\
\dot{N} &= \sigma_i n N_i
\end{aligned}$$

Simplest cases: $i = 1$ and $i = 2$

$$i = 1$$

$$\dot{n} = F - 2Dn^2 - DnN$$

$$\dot{N} = Dn^2$$

$$i = 2$$

$$\dot{n} = F - 2Dn^2 - DnN_2 + \frac{1}{\tau_2}N_2 - DnN$$

$$\dot{N}_2 = Dn^2 - DnN_2 - \frac{1}{\tau_2}N_2$$

$$\dot{N} = DnN_2$$

Simplest cases: $i = 1$ and $i = 2$

$$i = 1$$

$$\dot{n} = F - 2Dn^2 - DnN \approx 0 \; ; n \ll N \rightarrow n \approx \frac{F}{DN}$$

$$\dot{N} = Dn^2 \approx F\frac{F}{DN^2}$$

$$i = 2$$

$$\dot{n} = F - 2Dn^2 - DnN_2 + \frac{1}{\tau_2}N_2 - DnN \; ; \; n, N_2 \ll N \rightarrow n \approx \frac{F}{DN}$$

$$\dot{N}_2 = Dn^2 - DnN_2 - \frac{1}{\tau_2}N_2 \approx Dn^2 - \frac{1}{\tau_2}N_2 \approx 0 \rightarrow N_2 \approx (D\tau_2)n^2$$

$$\dot{N} = DnN_2 \approx D(D\tau_2)n^3$$

Simplest cases: $i = 1$ and $i = 2$

$$i = 1$$

$$n \approx \frac{F}{DN}$$

$$\frac{dN}{d\theta} \approx \frac{F}{DN^2} \; ; \; \theta = Ft$$

$$i = 2$$

$$n \approx \frac{D}{FN}$$

$$N_2 \approx (D\tau_2)n^2$$

$$\frac{dN}{d\theta} \approx \frac{D}{F}(D\tau_2)\left(\frac{F}{DN}\right)^3 = (D\tau_2)\left(\frac{F}{D}\right)^2 N^{-3}$$

Simplest cases: $i = 1$ and $i = 2$

$$i = 1$$

$$n \approx \frac{F}{DN}$$

$$N^2 \frac{dN}{d\theta} \approx \frac{F}{D} \rightarrow N^3 \approx \frac{F}{D} \rightarrow N \approx \left(\frac{F}{D}\right)^{1/3}$$

$$i = 2$$

$$n \approx \frac{D}{FN}$$

$$N_2 \approx (D\tau_2)n^2$$

$$\frac{dN}{d\theta} \approx (D\tau_2)\left(\frac{F}{D}\right)^2 N^{-3} \rightarrow N \approx (D\tau_2)^{1/4}\left(\frac{F}{D}\right)^{1/2}$$

General *i*

Assuming stationarity ($\dot{N}_s = 0$) one finds the solution

$$N_s = \left(\prod_{k=2}^{s} \sigma_{k-1} \tau_k \right) n^s.$$

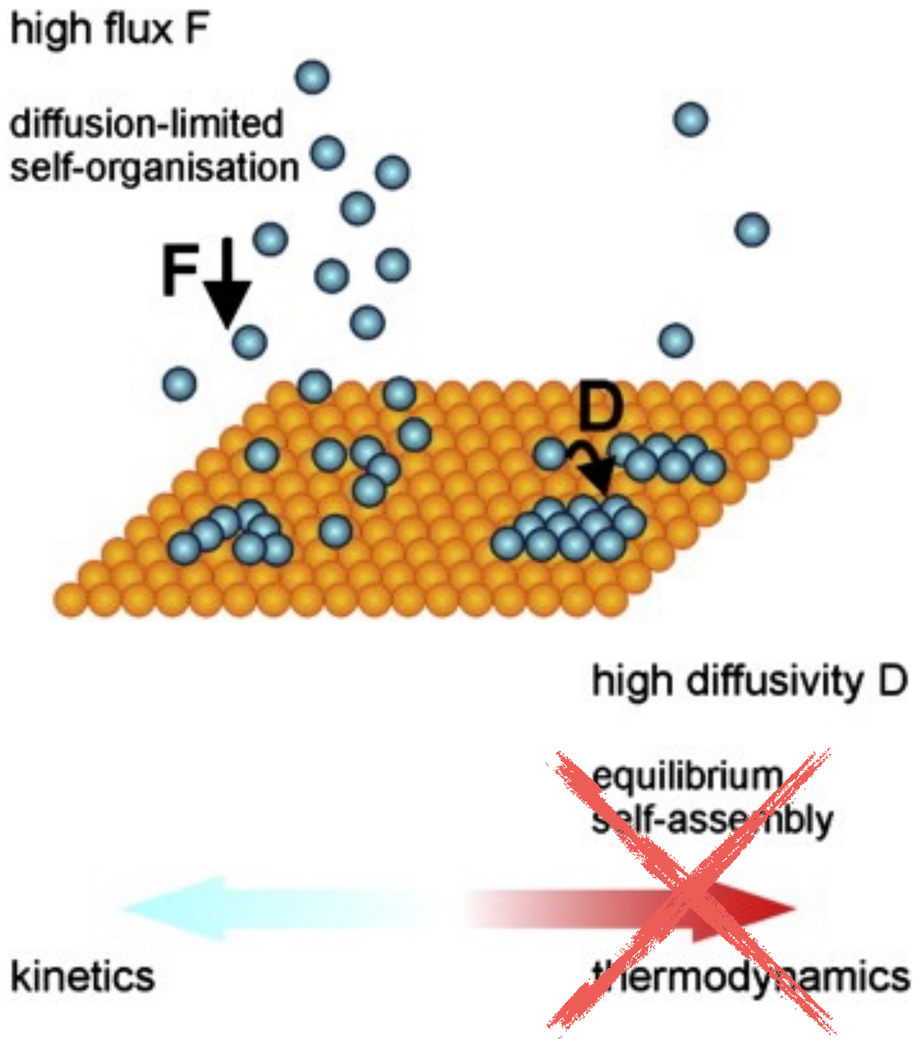
Integrating, we obtain

$$N \sim \left(\frac{F}{D} \right)^{i/(i+2)} \mathrm{e}^{E_i/[k_B T(i+2)]} = \left(\frac{F}{D_0} \right)^{i/(i+2)} \exp \left[\frac{iE_D + E_i)}{(i+2) k_B T} \right],$$

where E_D is the hopping energy barrier and E_i is the cohesion energy of a cluster of size i (the critical nucleus in this approach.)

Scaling!

$$N \sim \left(\frac{F}{D}\right)^{i/(i+2)}$$



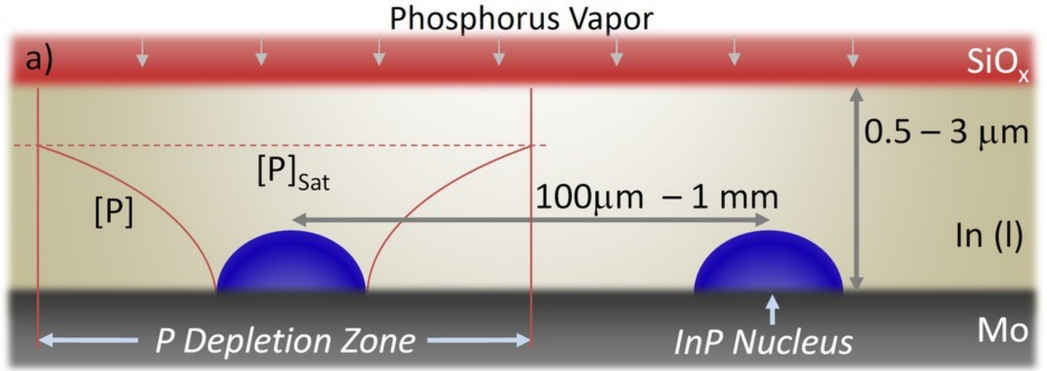
Scaling!

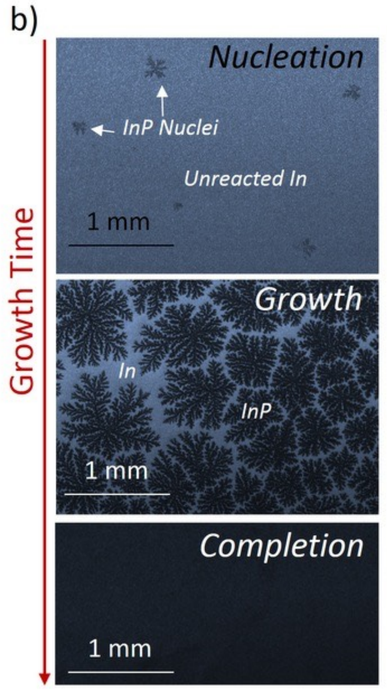
$$N \sim \left(\frac{F}{D}\right)^{i/(i+2)}$$

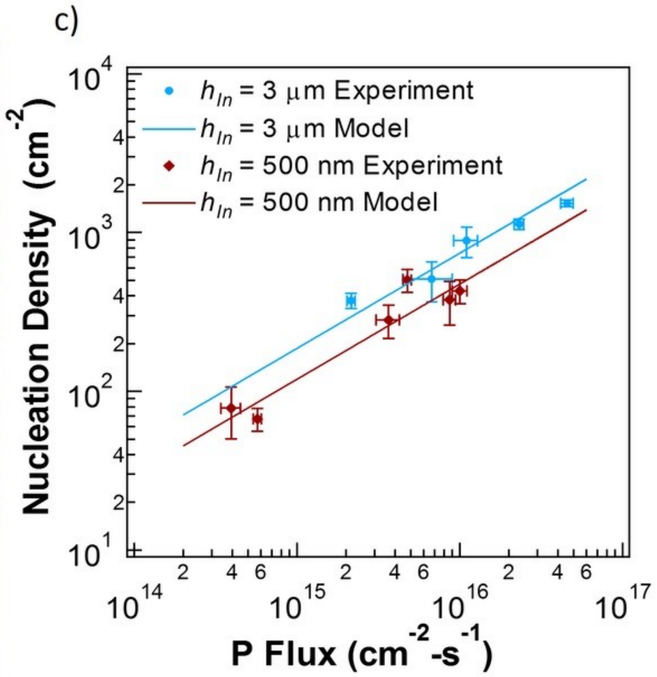
“Byproduct”: measuring diffusion coefficient by counting islands

A direct thin-film path towards low-cost large-area III-V photovoltaics

Rehan Kapadia[1,2*], Zhibin Yu[1,2*], Hsin-Hua H. Wang[1,2], Maxwell Zheng[1,2], Corsin Battaglia[1,2], Mark Hettick[1,2], Daisuke Kiriya[1,2], Kuniharu Takei[1,2], Peter Lobaccaro[2,3], Jeffrey W. Beeman[2], Joel W. Ager[2], Roya Maboudian[3], Daryl C. Chrzan[2,4] & Ali Javey[1,2]

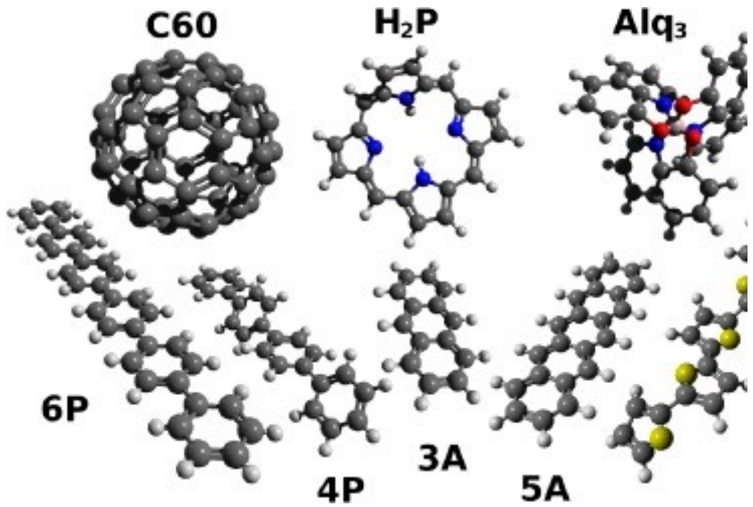


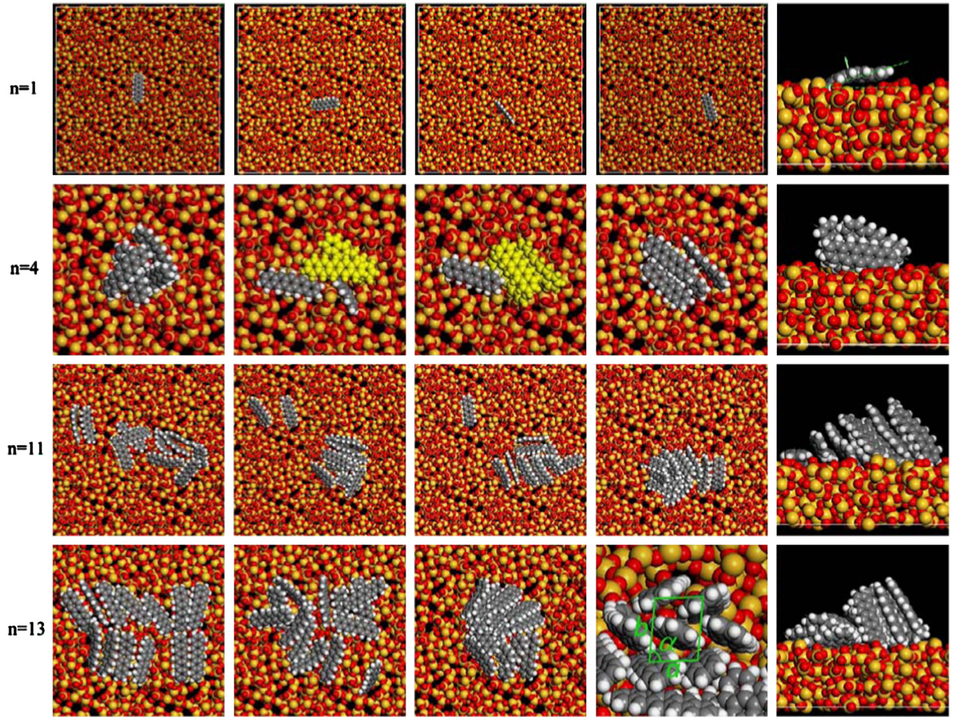




SCIENTIFIC REPORTS | 3 : 2275 | DOI: 10.1038/srep02275

Organic molecules!

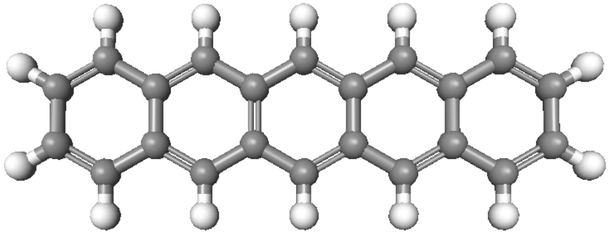




Journal of Crystal Growth 405 (2014) 73–80

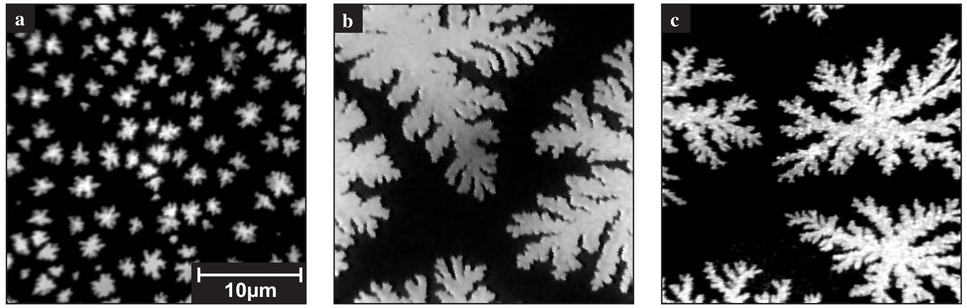
Molecular orientation transformation of pentacene on amorphous SiO_2: A computational study on the initial growth stage of physical vapor deposition

Yuanqi Zeng, Bo Tao*, Zhouping Yin



Growth dynamics of pentacene thin films

Frank-J. Meyer zu Heringdorf, M. C. Reuter & R. M. Tromp



Pentacene•SiO_2 Pentacene•Si(001) Pentacene•Cyclohexene•Si(001)

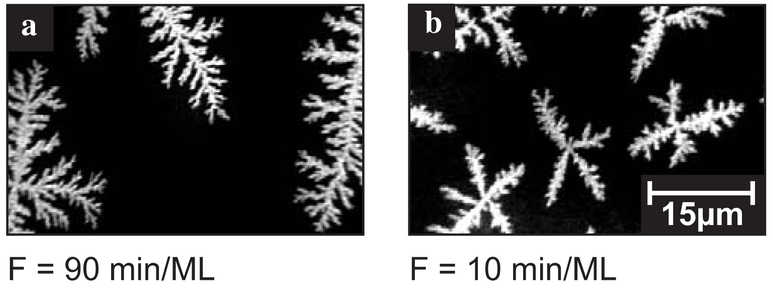
Appl. Phys. A 78, 787–791 (2004)
DOI: 10.1007/s00339-003-2432-x

Applied Physics A
Materials Science & Processing

F.-J. MEYER ZU HERINGDORF ✉,*
M.C. REUTER
R.M. TROMP

The nucleation of pentacene thin films

IBM T.J. Watson Research Center, Yorktown Heights, P.O. Box 218, NY 10598, USA



F = 90 min/ML F = 10 min/ML

F = 8 min/ML F = 4.5 min/ML

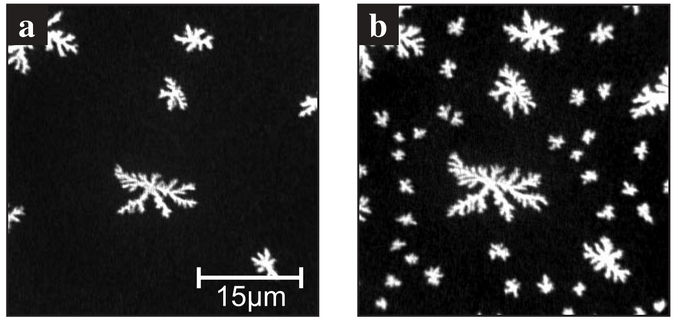


FIGURE 4 Influence of the deposition rate on the nucleation density for pentacene on cyclohexene on Si(001). **a** typical PEEM image after island nucleation, **b** PEEM image after additional nuclei were formed by an increased rate

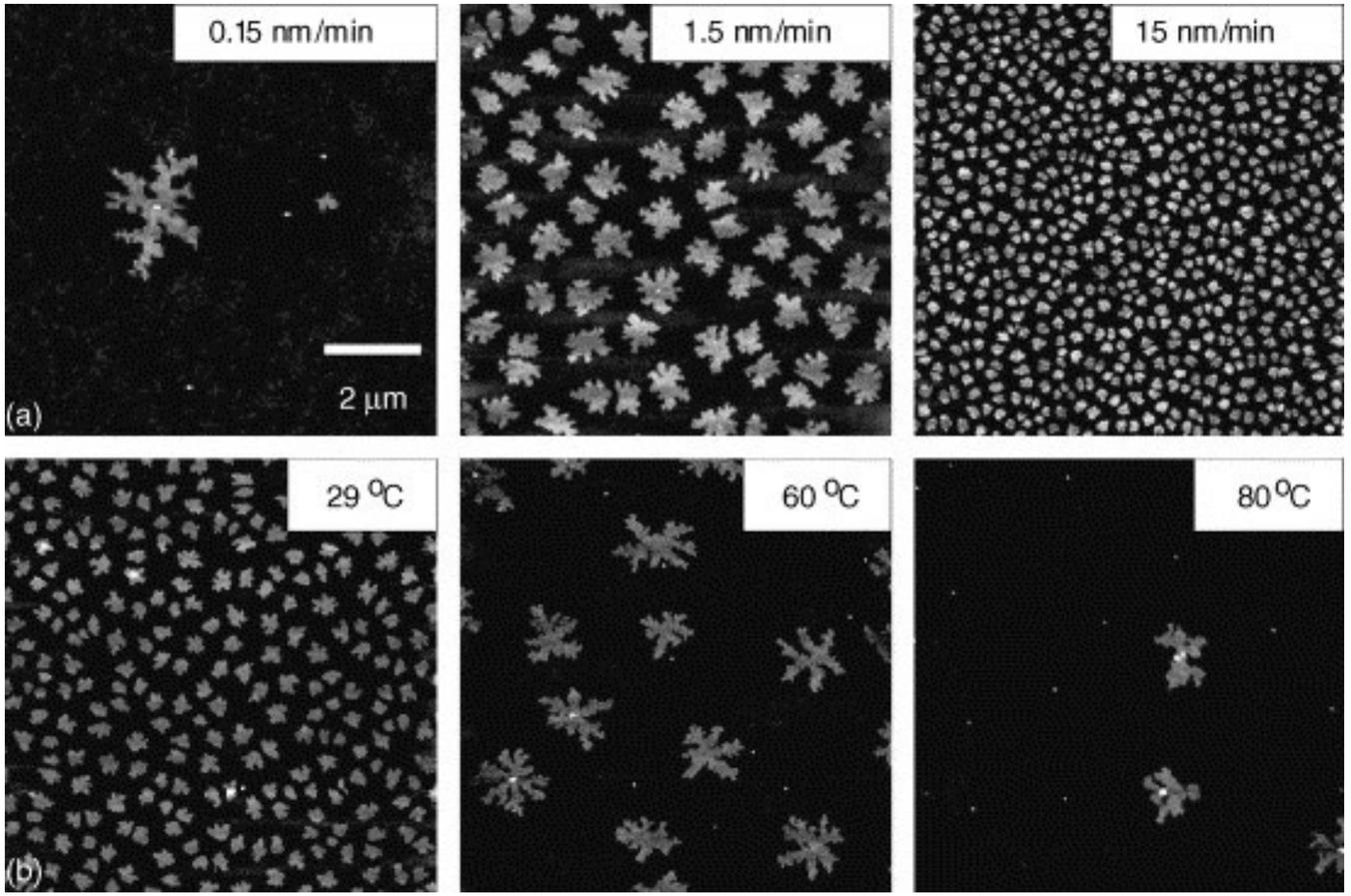


Fig. 1 AFM surface topography (10 μm × 10 μm) of 0.5 nm-thick pentacene films grown on a 200 nm-thick SiO 2 substrate (a) at various deposition rate for a fixed substrate temperature of 65 °C and (b) at different substrate temperatures for a fixed deposit...

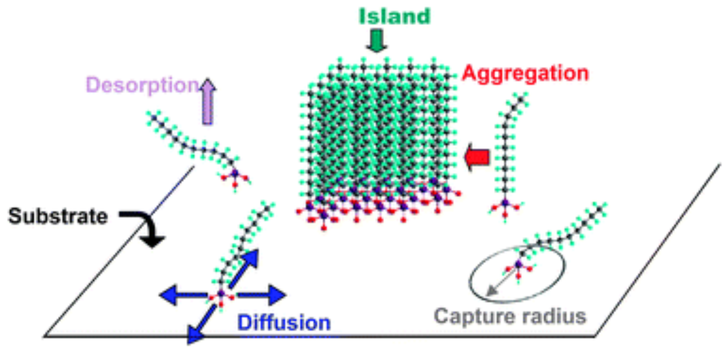
Sirapat Pratontep , Martin Brinkmann , Frank Nüesch , Libero Zuppiroli

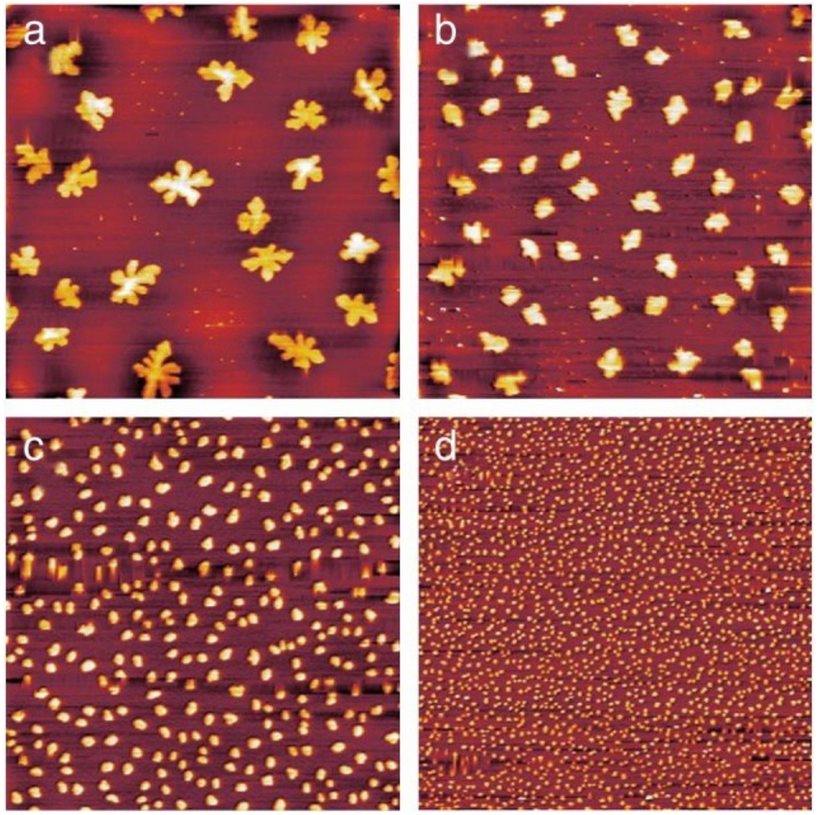
Nucleation and growth of ultrathin pentacene films on silicon dioxide: effect of deposition rate and substrate temperature

Synthetic Metals, Volume 146, Issue 3, 2004, 387 - 391

http://dx.doi.org/10.1016/j.synthmet.2004.08.017

Deposition, diffusion, nucleation and aggregation





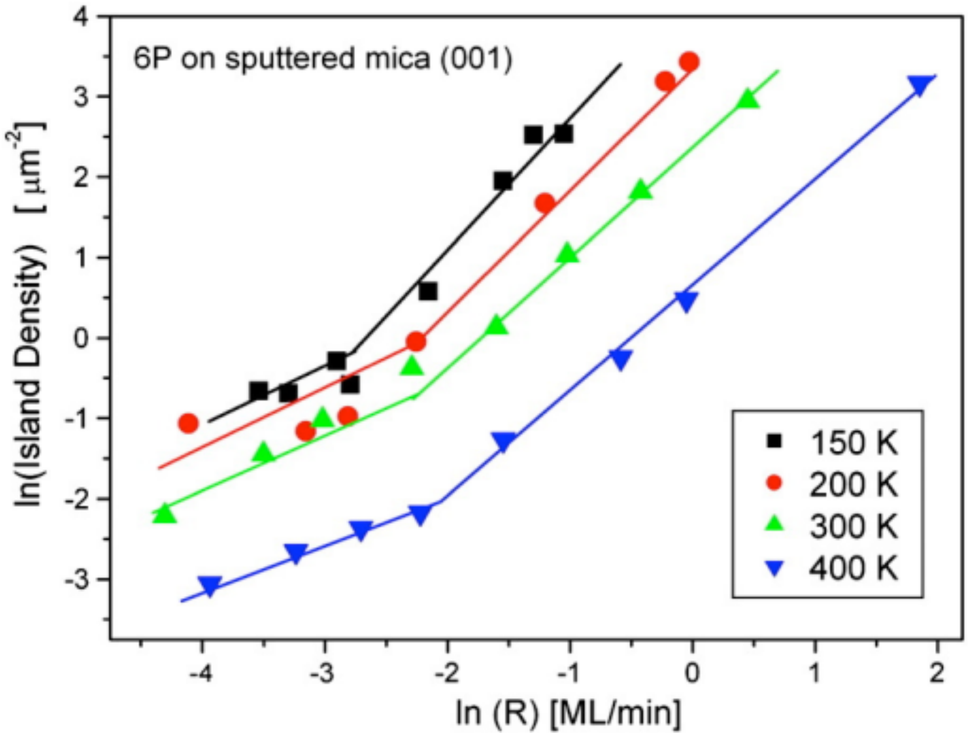
Surface Science Letters

Attachment limited versus diffusion limited nucleation of organic molecules: Hexaphenyl on sputter-modified mica

L. Tumbek, A. Winkler *

Scaling?

$$N \sim \left(\frac{F}{D}\right)^{i/(i+2)}$$



Surface Science Letters

Attachment limited versus diffusion limited nucleation of organic molecules: Hexaphenyl on sputter-modified mica

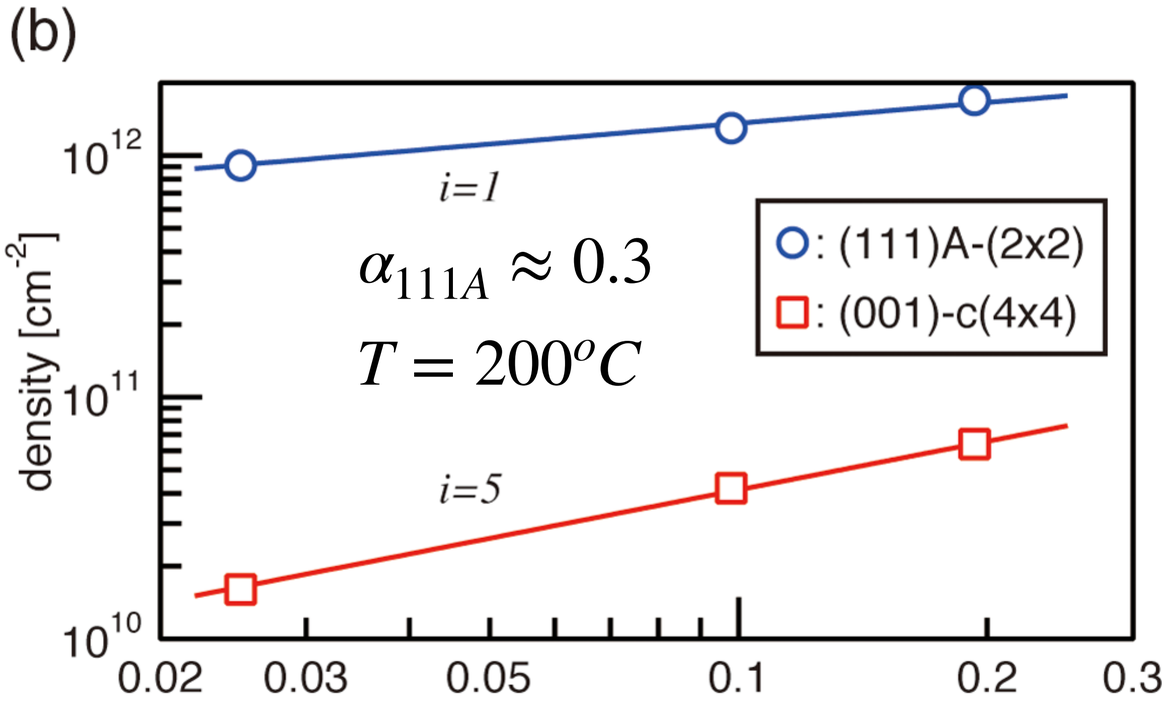
L. Tumbek, A. Winkler *

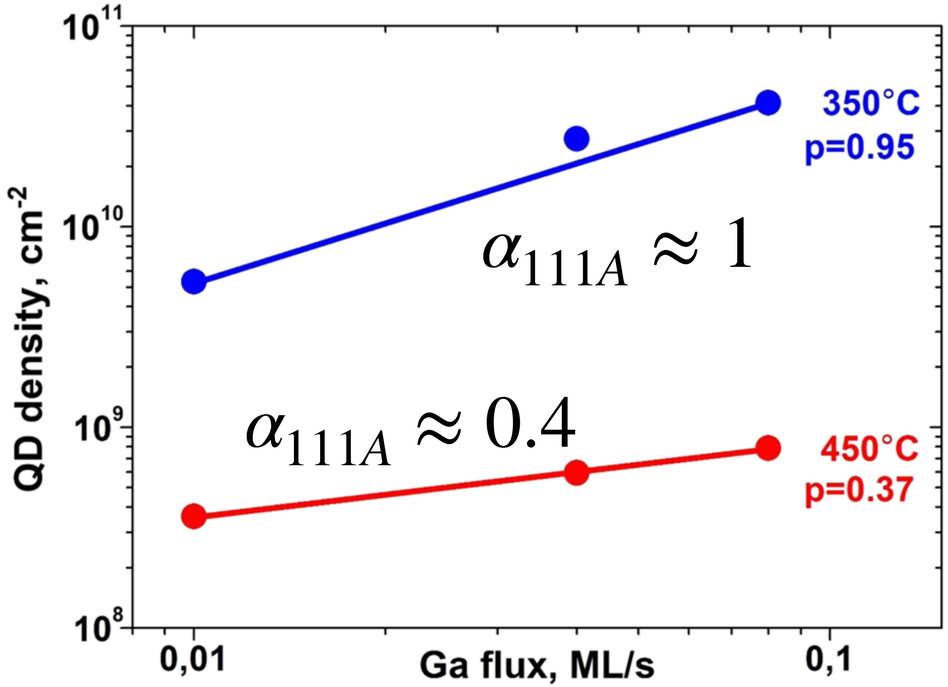
Different exponents
may imply
different aggregation
processes
Diffusion Limited (DLA)
Attachment Limited (ALA)
3D Clusters (3D) …

$$\alpha_{\mathrm{DLA}} = i/(i+2)$$

$$\alpha_{\mathrm{ALA}} = 2i/(i+3)$$

$$\alpha_{3D} = 2i/(2i+5)$$





Ga droplets on GaAs(111)A 2º vicinal

Can one extract from the islands pattern more information about the nucleation process?

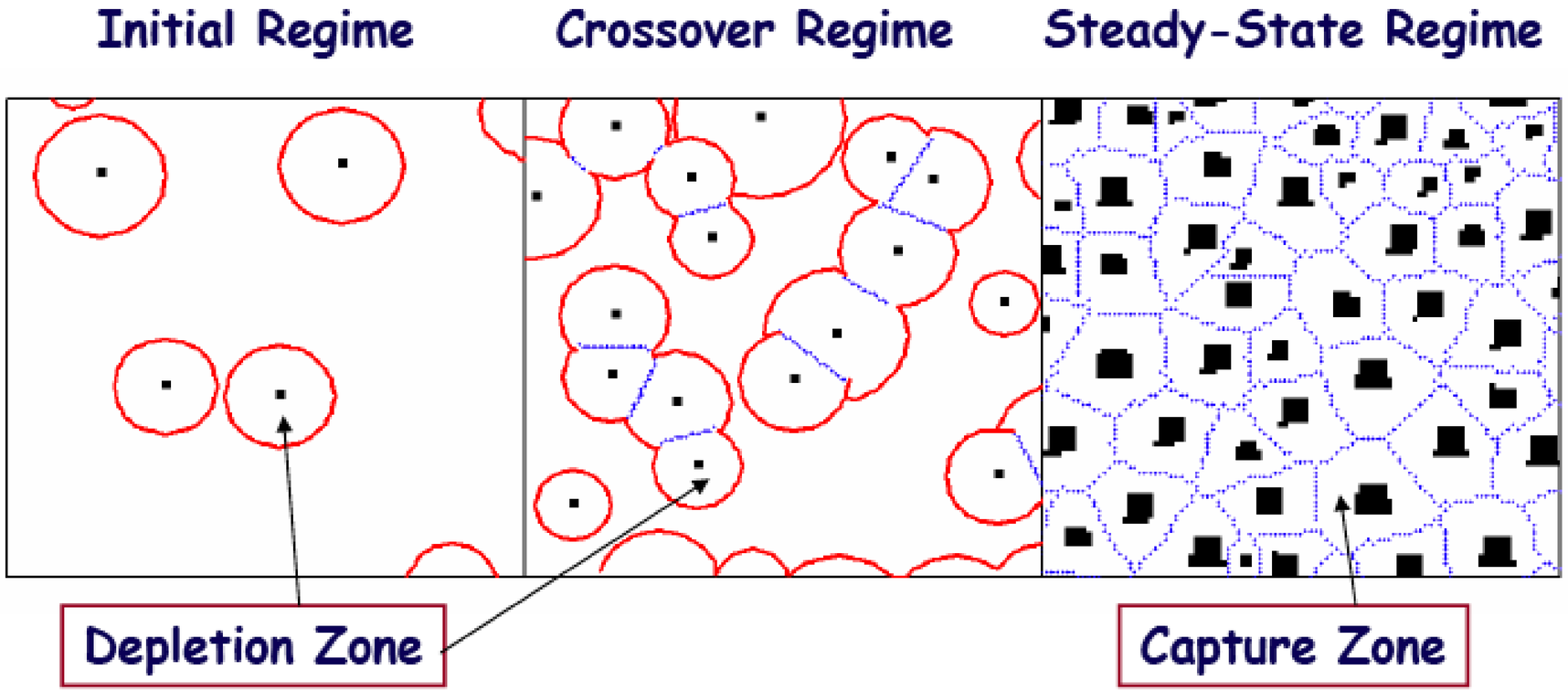
Average island density

$$N = \frac{1}{\langle A \rangle}$$

Average area per island

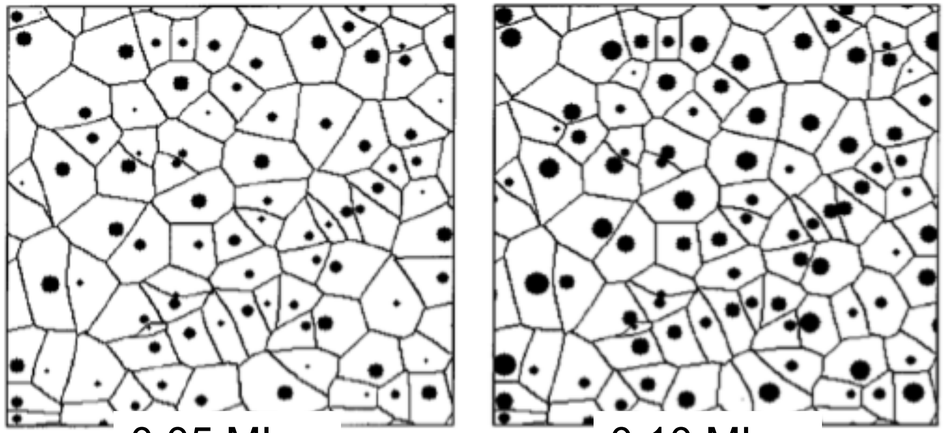
Beyond island densities

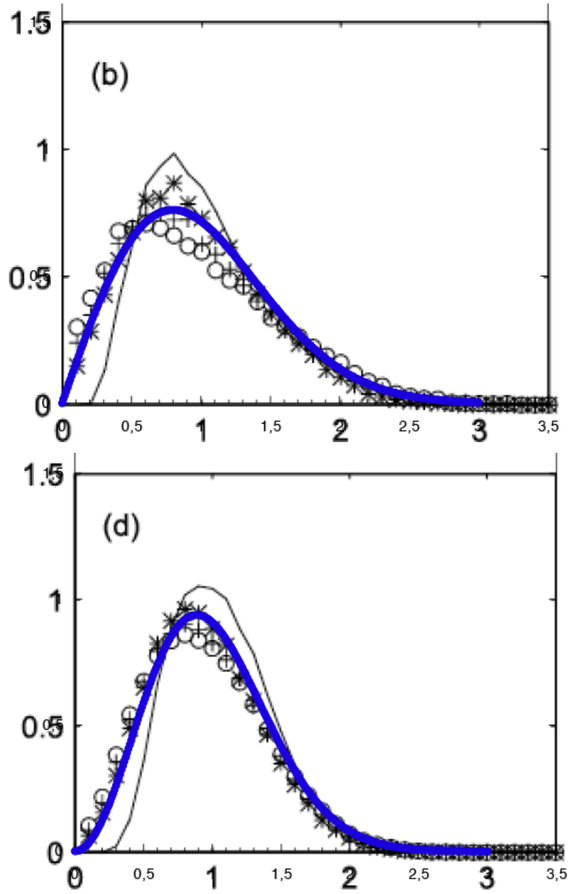
Area fluctuations:
Capture Zone Distribution
(CZD)



Simulations of i=0,1 *Circular* Islands

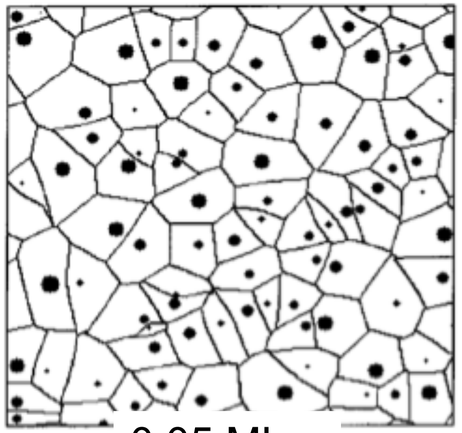
Mulheran & Blackman, PRB 53 (96) 10261



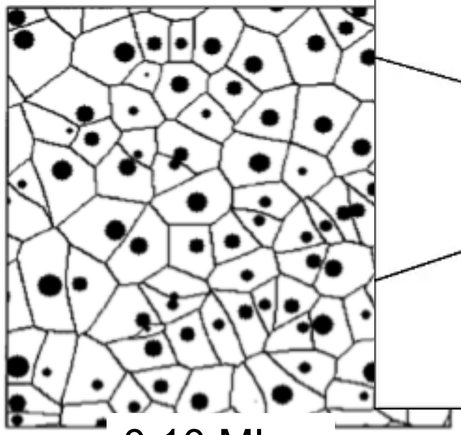


Simulations of i=0,1

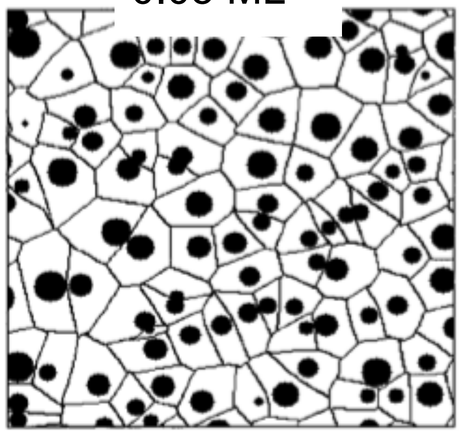
Mulheran & Blackman, Pl



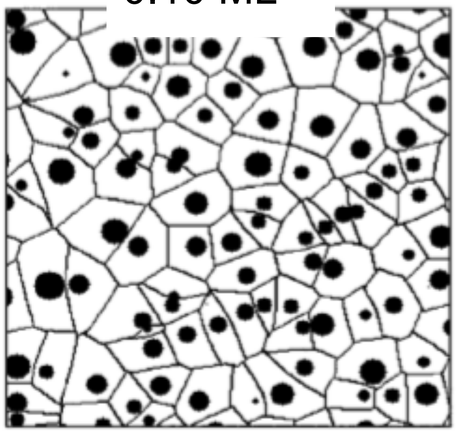
0.05 ML



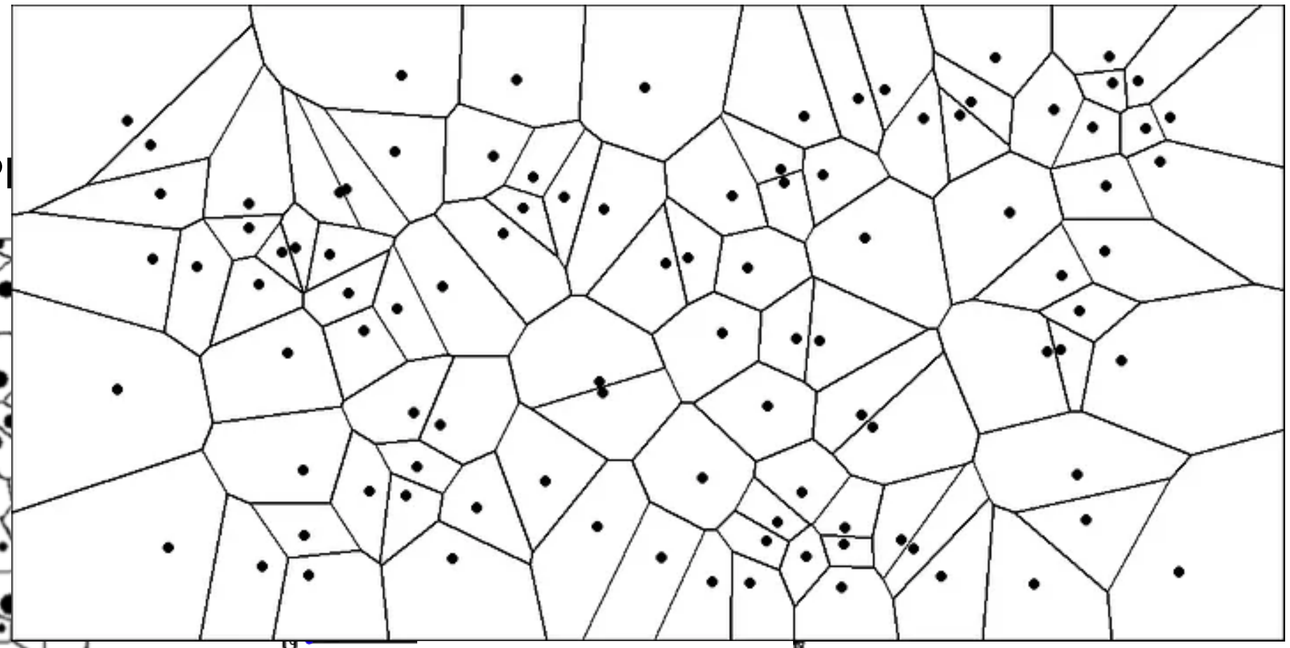
0.10 ML



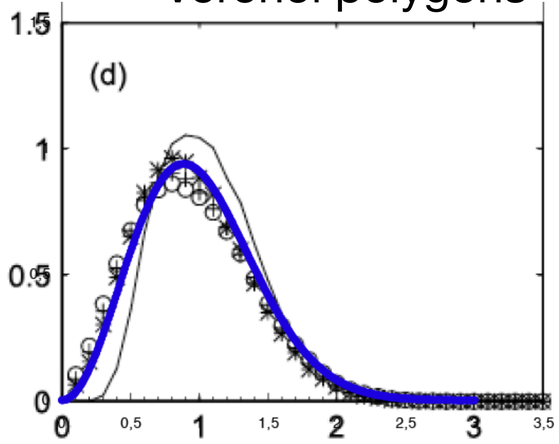
0.20 ML



0.15 ML

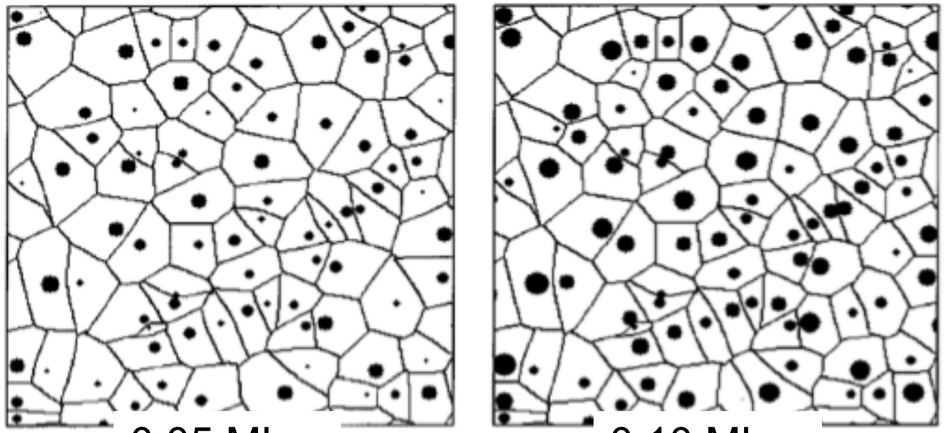


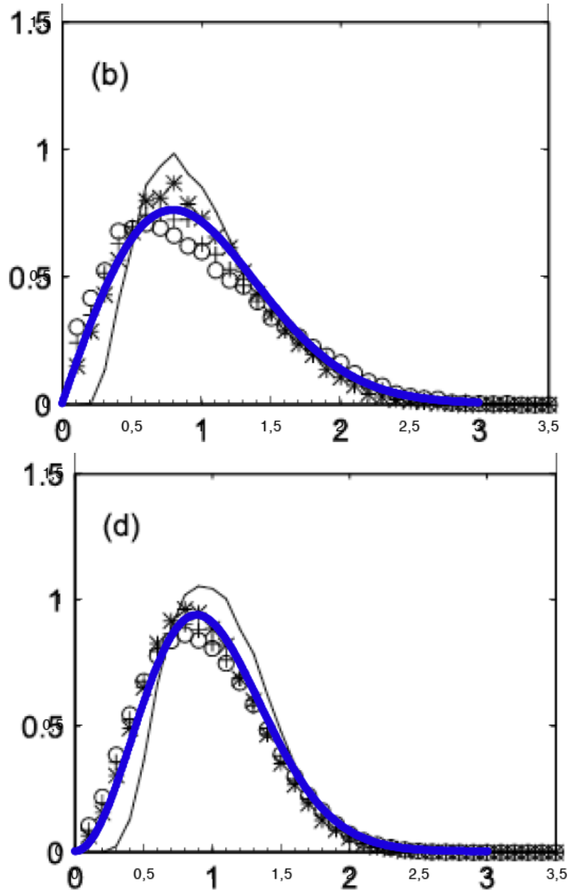
Voronoi polygons



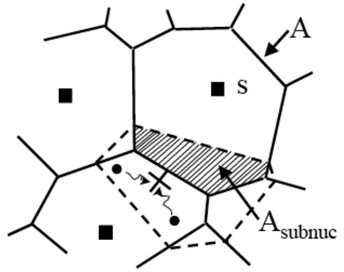
Simulations of i=0,1 *Circular* Islands

Mulheran & Blackman, PRB 53 (96) 10261





A phenomenological model for the CZD



Nucleation rate between islands

$\dot{N}(A)$

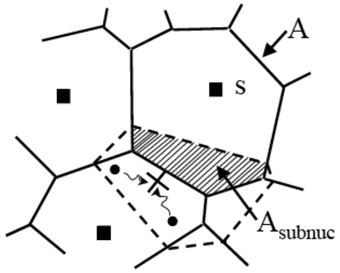
$$\dot{N}_{i+1} \approx DnN_i \approx Dnn^i = Dn^{i+1}$$

PRL **99,** 226102 (2007) PHYSICAL REVIEW LETTERS week ending 30 NOVEMBER 2007

Capture-Zone Scaling in Island Nucleation: Universal Fluctuation Behavior

Alberto Pimpinelli[1,2,*] and T. L. Einstein[2,†]

A phenomenological model for the CZD



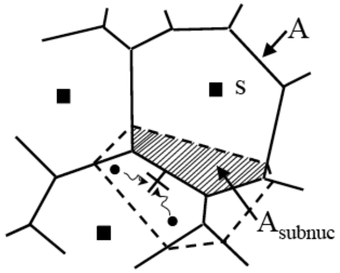
$$\dot{N}(A) \sim D \int_A dr r [n(r)]^{i+1} \sim A^{i+2}$$

$$\dot{N}(A) \sim D\bar{n}^{i+1} P(s), \qquad s = A/\langle A \rangle$$

↳ **probability of a capture zone having area *s* = A/<A>**

$$\bar{n} = (F/D)^{i+1} \langle A \rangle^{i+1}$$

A phenomenological model for the CZD



$$\dot{N}(A) \sim D \int_A dr r [n(r)]^{i+1} \sim A^{i+2}$$

$$\dot{N}(A) \sim D\bar{n}^{i+1} P(s), \qquad s = A/\langle A \rangle$$

$$\hookrightarrow P(s) \propto s^{i+2} = (A/\langle A \rangle)^{i+2}$$

$$\bar{n} = (F/D)^{i+1} \langle A \rangle^{i+1}$$

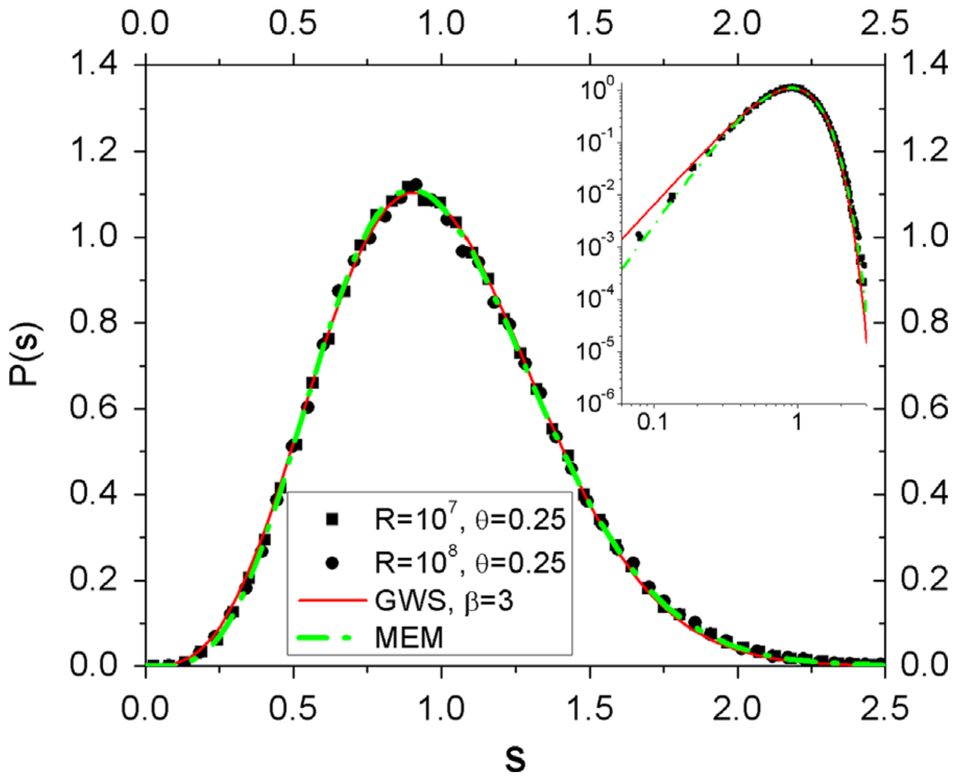
A phenomenological model for the CZD

$$\beta_{\mathrm{DLA}} = i + 2$$

$$P(s) = a_\beta s^\beta \exp(-b_\beta s^2)$$

Wigner distribution

$$\beta_{\mathrm{ALA}} = (i + 3)/2$$



Experiments:
III-V droplet epitaxy

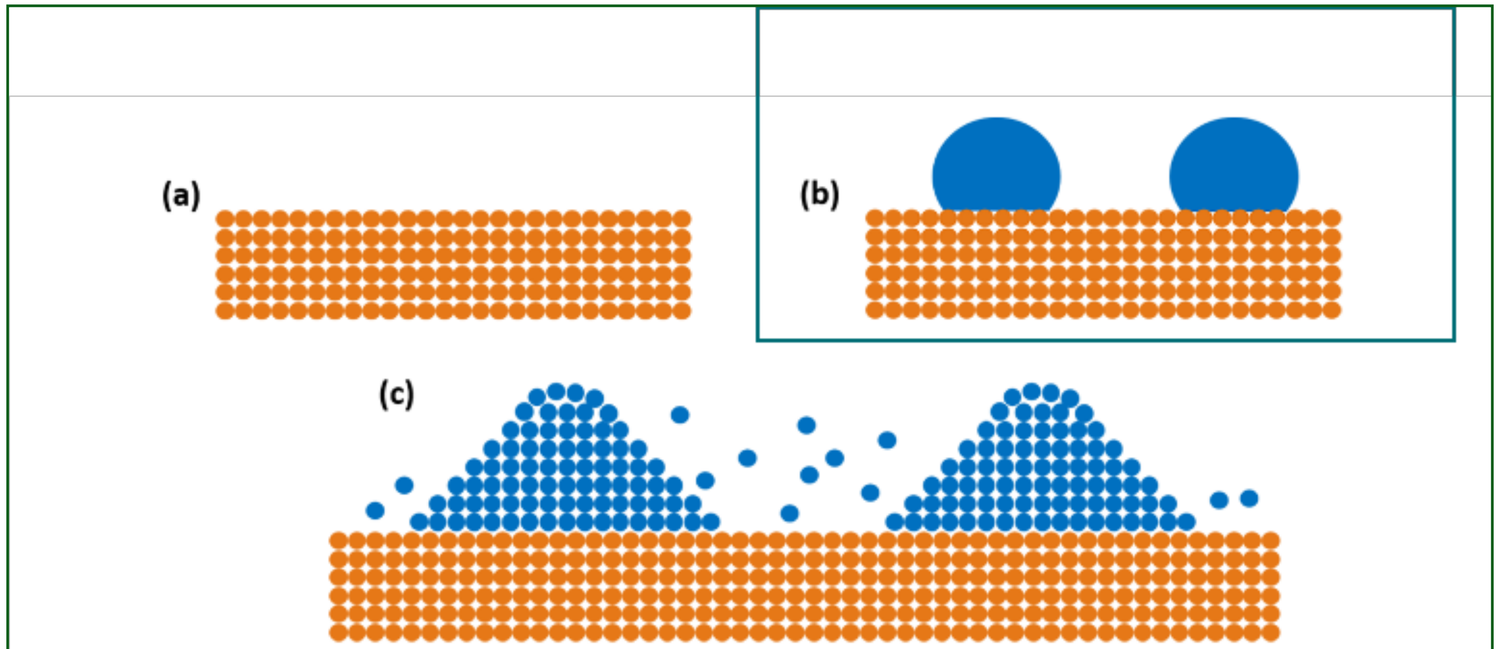


Figure 2. Schematic process showing the formation of DEQDs: (**a**) buffer layer; (**b**) deposition of group III droplets on the surface; (**c**) crystallization of formed droplets in group V rich environment.

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$$\beta_{\mathrm{ALA}} = (i+3)/2$$

$$\beta_{\mathrm{DLA}} = i+2$$

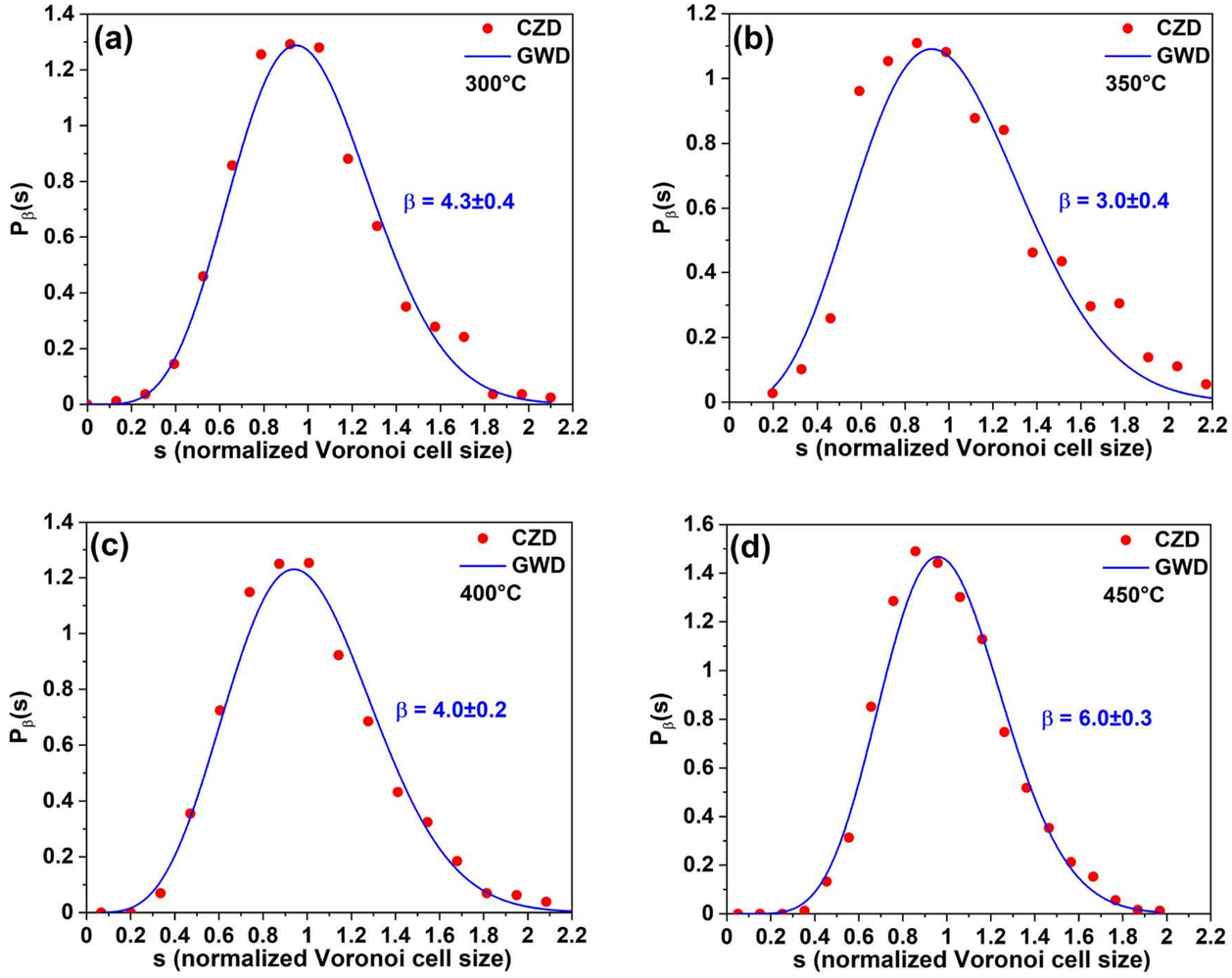
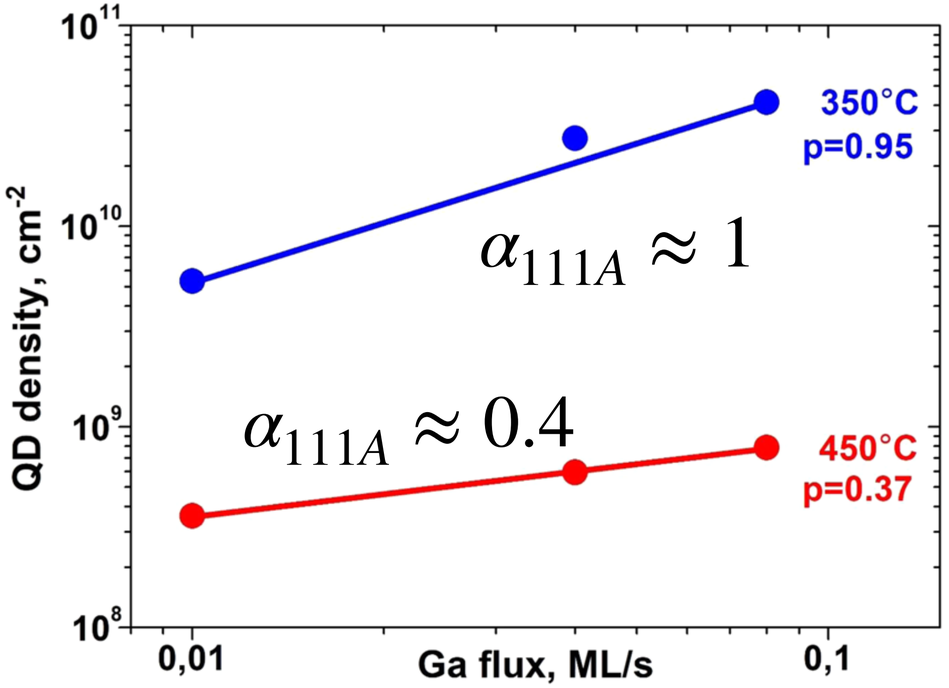


Figure 3. CZDs of the samples (**a**) T1, (**b**) T2, (**c**) T3, and (**d**) T4, fitted by the GWD.

Sample	β	$i = \beta - 2$
T1 (300 °C)	4.3 ± 0.4	2.3 ± 0.4
T2 (350 °C)	3.0 ± 0.4	1.0 ± 0.4
T3 (400 °C)	4.0 ± 0.2	2.0 ± 0.2
T4 (450 °C)	6.0 ± 0.3	4.0 ± 0.3

Artur Tuktamyshev[1,3], Alexey Fedorov[2,3], Sergio Bietti[1,3], Stefano Vichi[1,3], Riccardo Tambone[1,3], Shiro Tsukamoto[1,3] & Stefano Sanguinetti[1,3]

Ga droplets on GaAs(111)A 2º vicinal

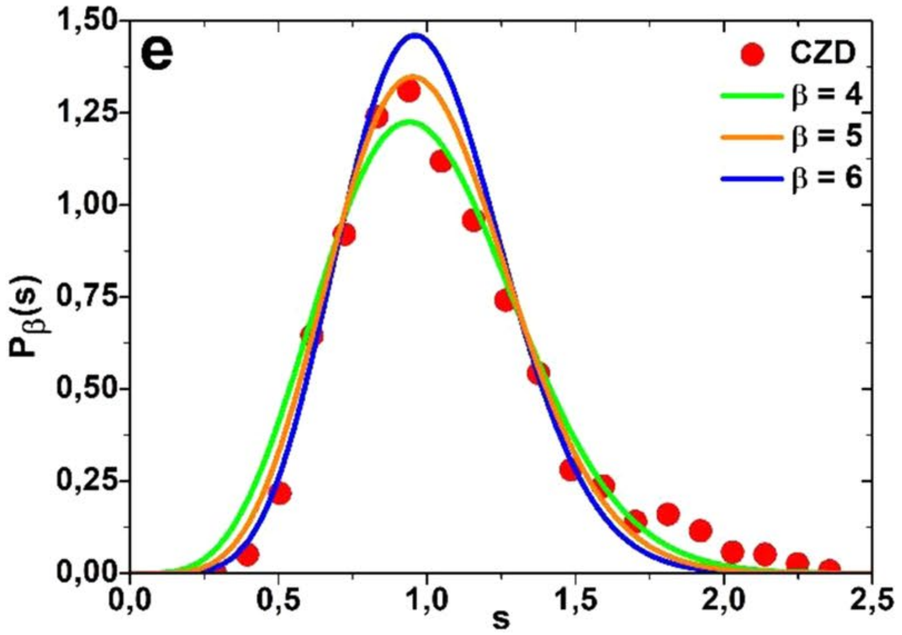


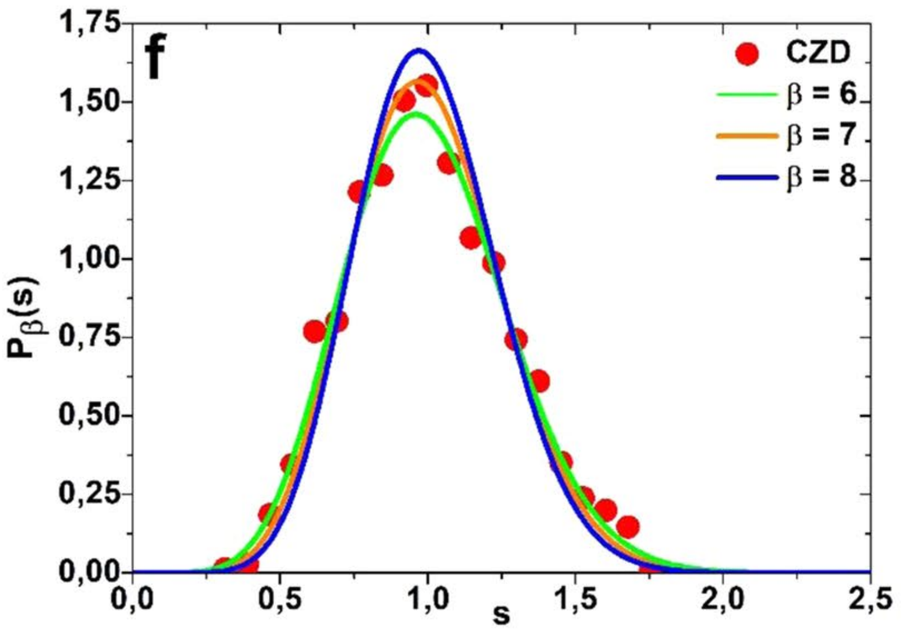
Temperature Activated Dimensionality Crossover in the Nucleation of Quantum Dots by Droplet Epitaxy on GaAs(111)A Vicinal Substrates

Artur Tuktamyshev[1], Alexey Fedorov[2], Sergio Bietti[1], Shiro Tsukamoto[1] & Stefano Sanguinetti[1]

SCIENTIFIC REPORTS | (2019) 9:14520 | https://doi.org/10.1038/s41598-019-51161-5

Ga droplets on GaAs(111)A
2º vicinal





$$\beta_{300^0C} \approx 5$$

$$i_{DLA} \approx 3$$

$$i_{ALA} \approx 4$$

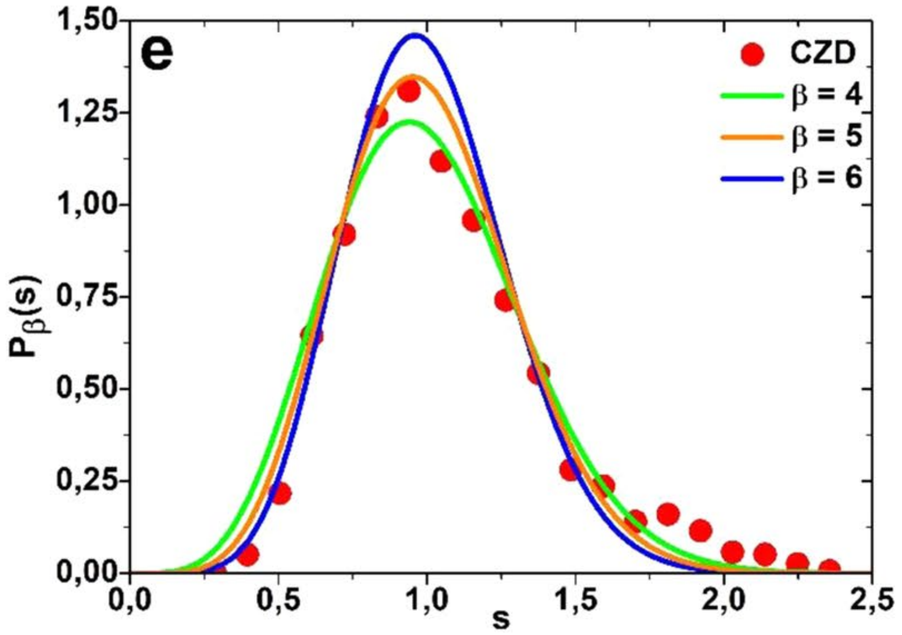
$$\beta_{450^0C} \approx 7$$

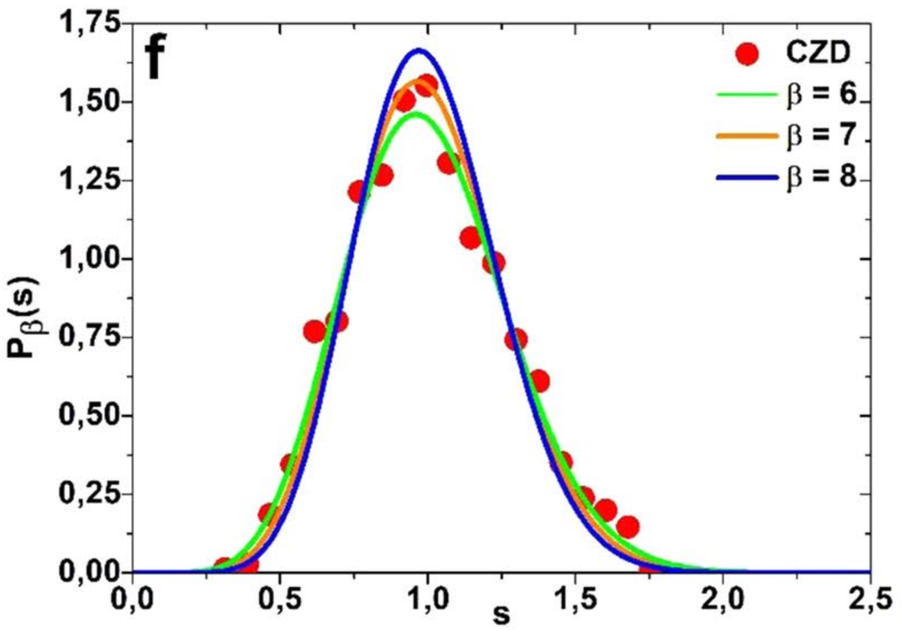
$$i_{DLA} \approx 5$$

$$i_{ALA} \approx 6$$

$$\alpha_{3D}(2\beta_{3D} + 1) = 2i$$

Ga droplets on GaAs(111)A
2º vicinal





$$\beta_{300^0C} \approx 5$$

$$i_{DLA} \approx 3$$

$$i_{ALA} \approx 4$$

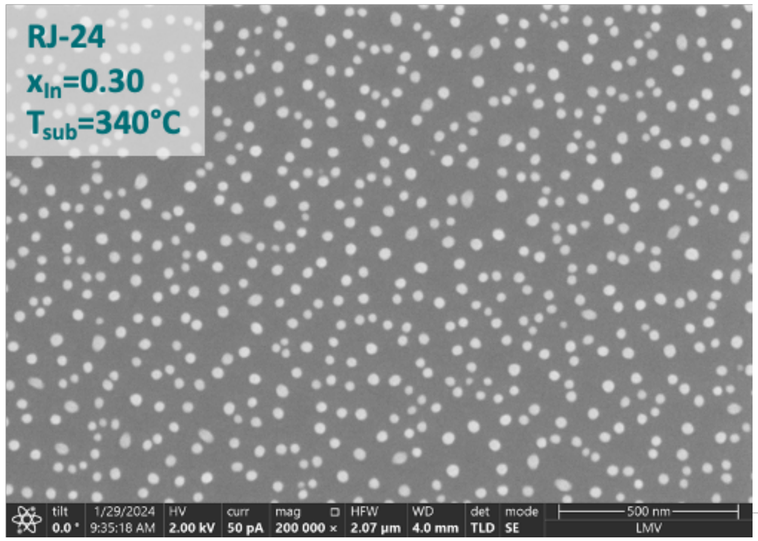
$$\beta_{450^0C} \approx 7$$

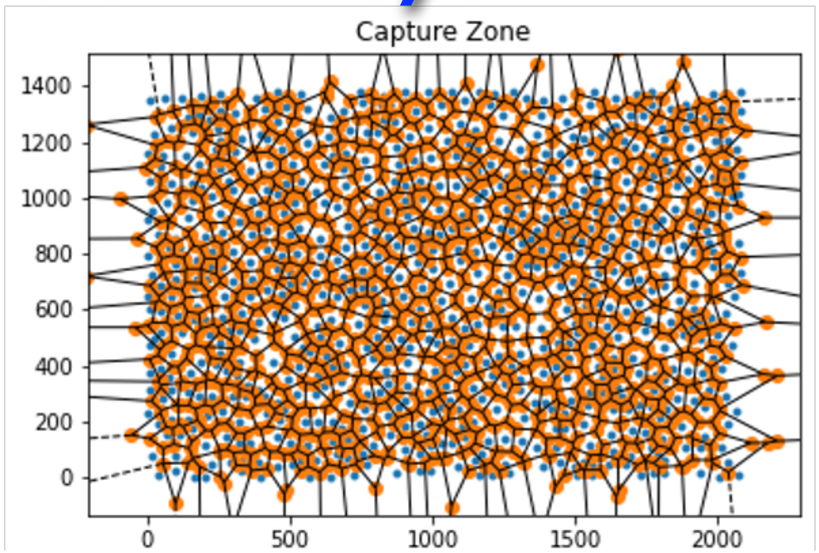
$$i_{DLA} \approx 5$$

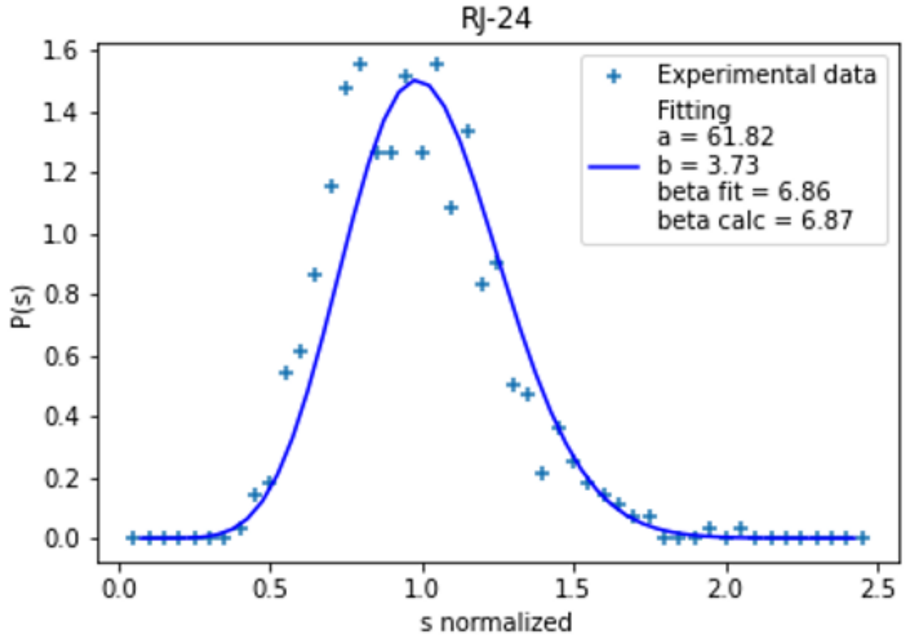
$$i_{ALA} \approx 6$$

$$0.4(2 \times 7 + 1) = 6 \rightarrow i_{3D} = 3$$

Tuning nucleation: alloys







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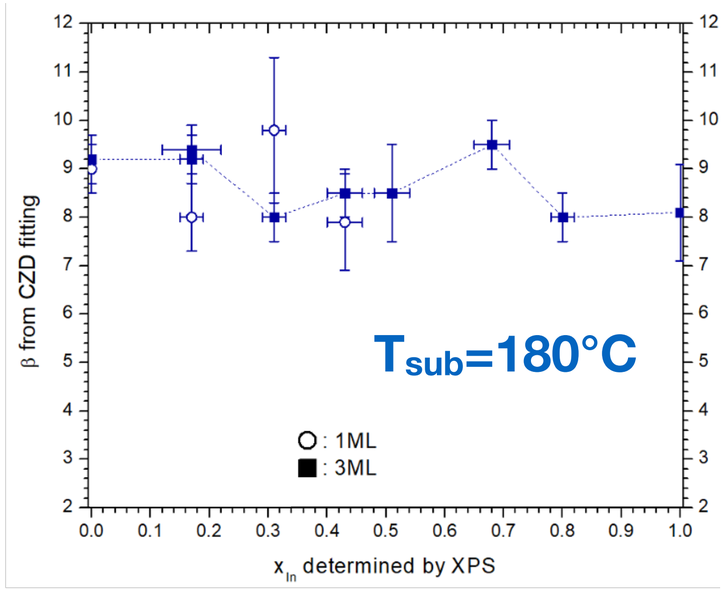
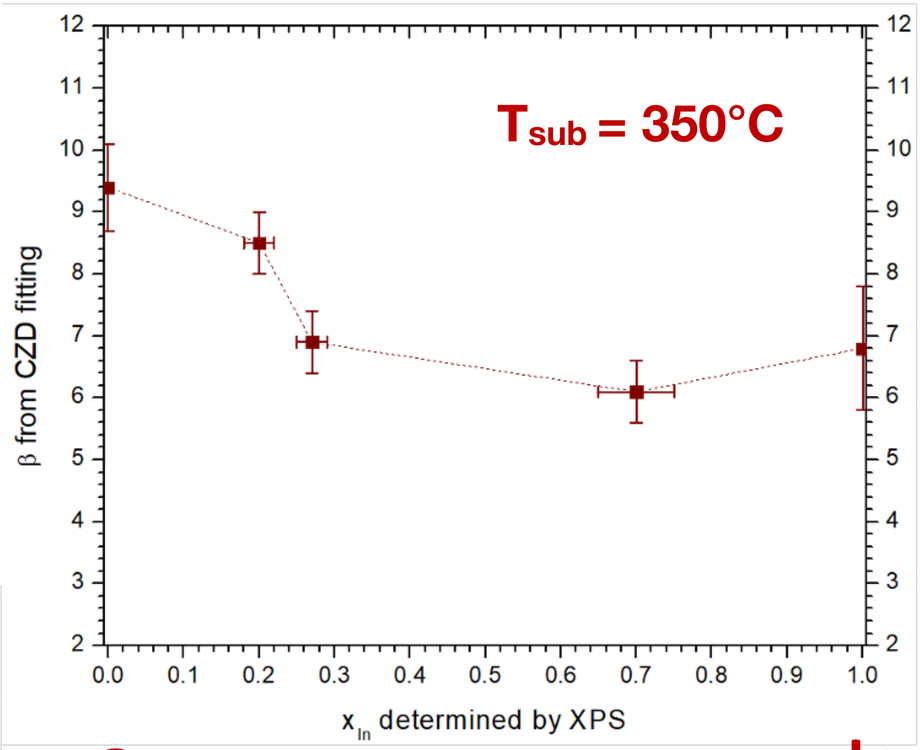
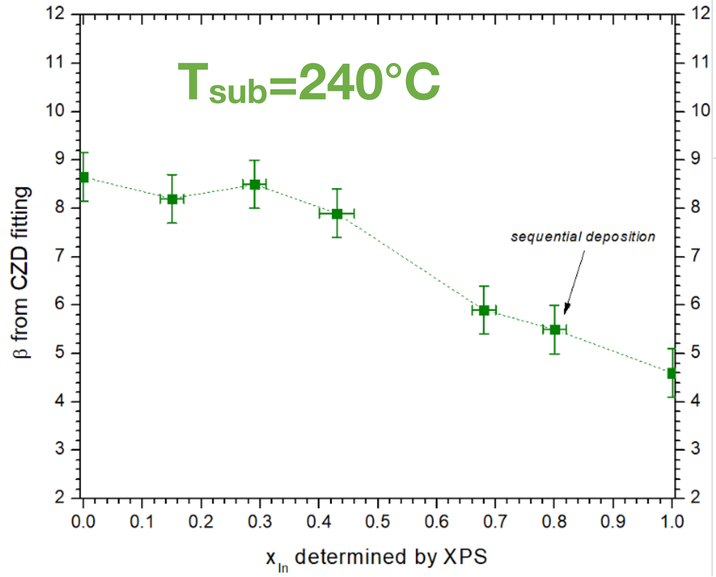
Tuning nucleation: alloys







Ga

In

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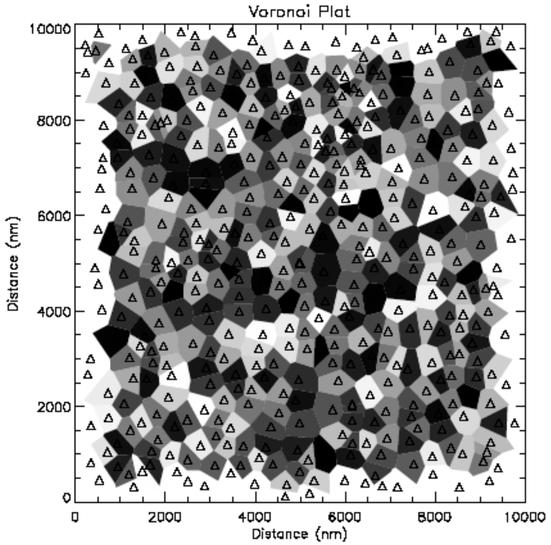
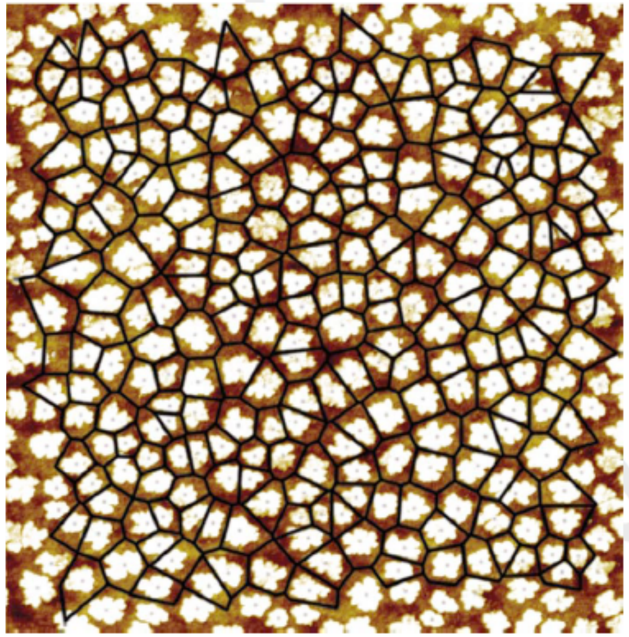
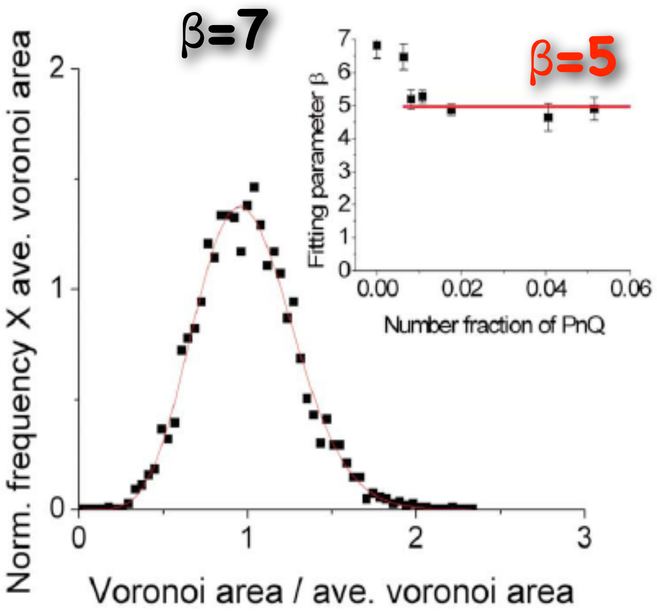
Tuning nucleation: impurities

experiments: pentacene islands with quinone impurities







PHYSICAL REVIEW B 77, 205328 (2008)

Effect of impurities on pentacene island nucleation

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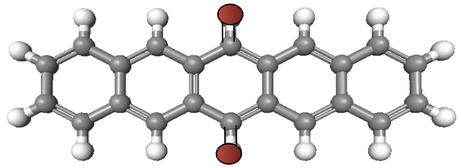
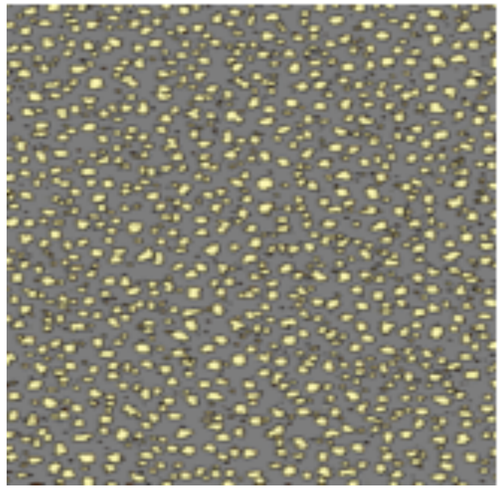
Physics Department and Materials Research Science and Engineering Center, University of Maryland, College Park, Maryland 20742-4111, USA
(Received 11 February 2008; published 27 May 2008)

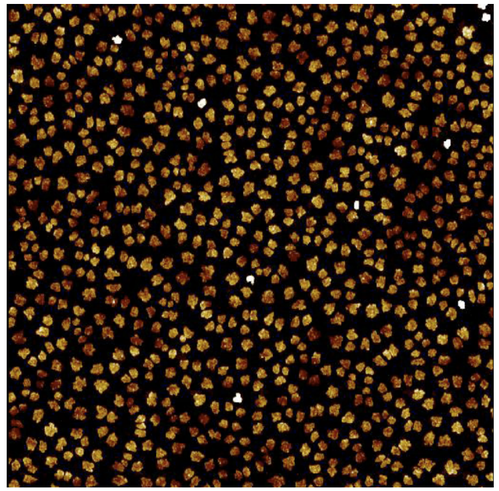


Tuning nucleation: impurities

Sim.

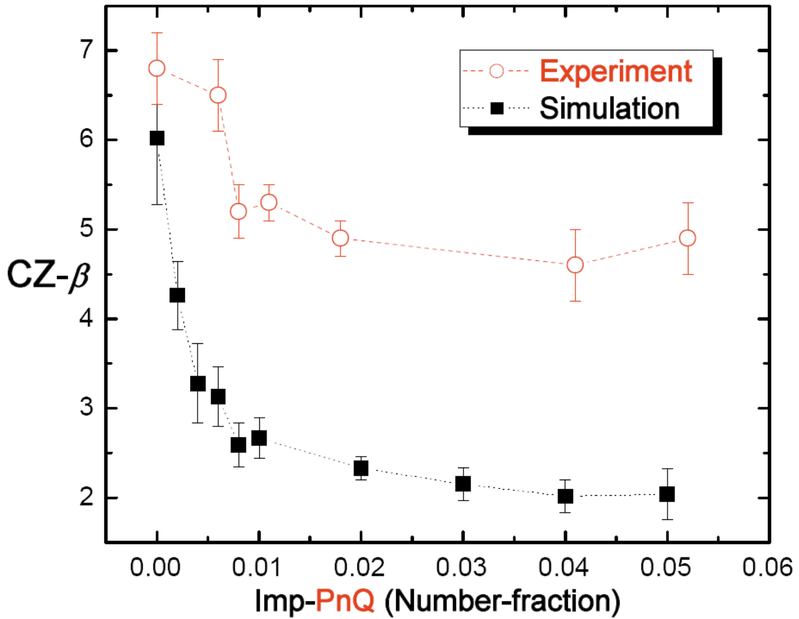


Exp.



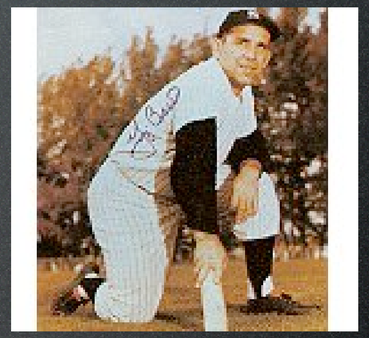
0.5 % Pentacene/PentaceneQuinone

B Conrad,et al. PRB 77, 205328 (2008)



Modeling nucleation: elasticity

In theory there is no difference between theory and practice. In practice there is.



Yogi Berra

Modeling nucleation: elasticity

Simulation flow chart

Hydrice Nzomo
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Initialise la condition d'arrêt du code en fonction du taux de couverture

On dénombre les atomes en surface en fonction de leur voisin

On calcule la probabilités P_0, P_1, P_2, P_3, … P_i , P_t

On tire un nombre aléatoire « r » uniformément repartie dans [0,1]

$0 < r < f/P_t$

$(\mathrm{f} + \sum_{i=0}^{k-1} P_i)/P_t < r < (\mathrm{f} + \sum_{i=0}^{k} P_i)/P_t$

Dépôt sur une position non occupée (i,j) de la surface

Diffusion d'un adatome sur le site (i,j)

Calcule le potentiel chimique de la position de l'atome choisis

Calcul le potentiel chimique des voisins (corrige de E_h si marche)

Calcul des p_d de diffusion pour chaque voisin

Choix de la direction de diffusion selon p_d (max ou selon le nombre aleatoir)

Cas de p_d :: Si p_d =0 configuration stable : désorption de l'atome (h(i, j) = h(i, j) – 1)

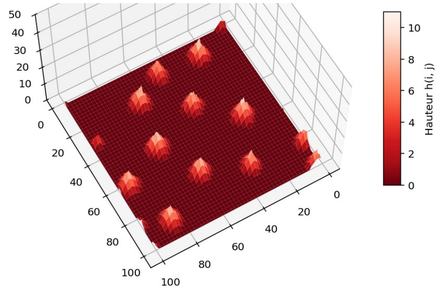
Mettre a jour le fichier contenant les positions des atomes et l'état de la surface

Effet élastique

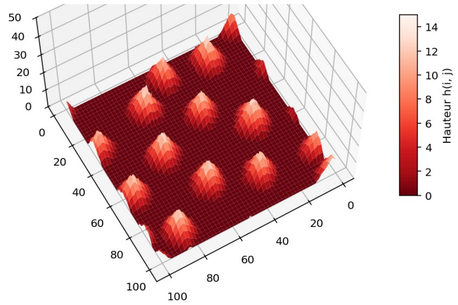
La direction de diffusion est choisir par un nombre aléatoire (ΔE_{el}=$E0 + E_{EL}(i,j) - E_{EL}(ni(d), nj(d))$)

$p(d) = D_0 * \exp(-(Ed + \Delta E_{el})/K_B T$

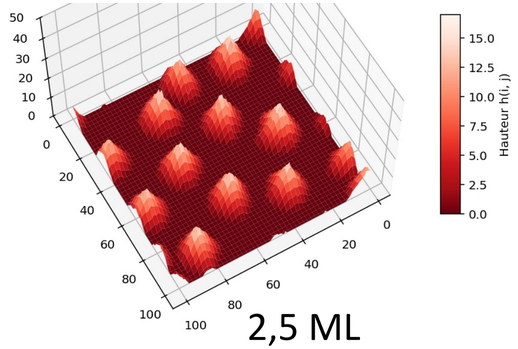
TAILLE DE LA GRILLE 100*100



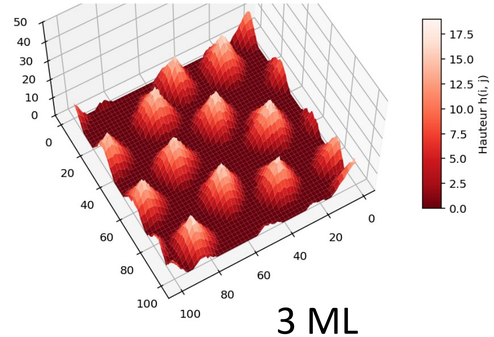
0,5 ML



1,5 ML

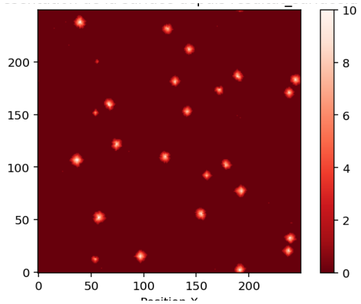


2,5 ML

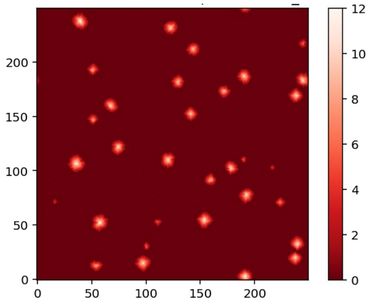


3 ML

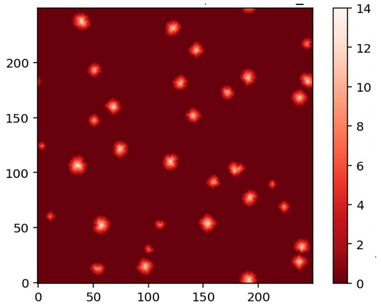
TAILLE DE LA GRILLE 250*250



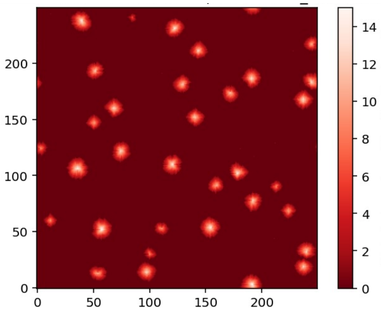
1/10 ML



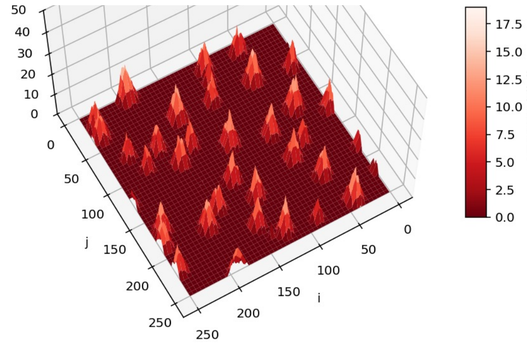
2/10 ML



3/10 ML

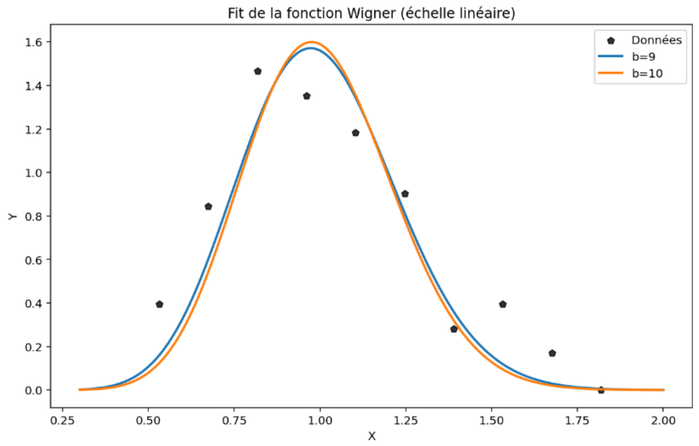


4/10 ML

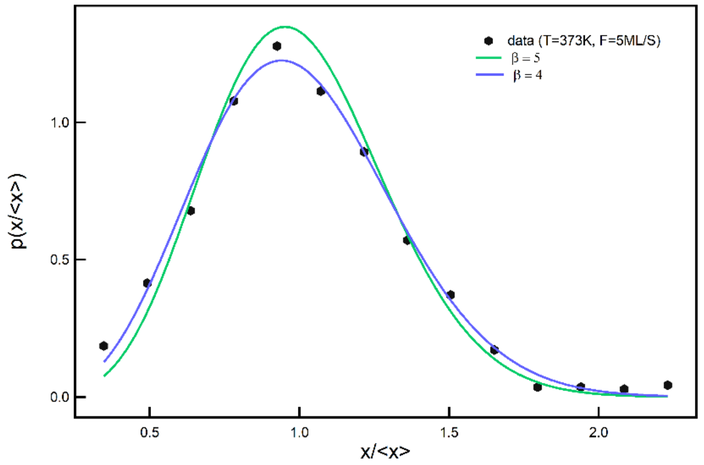


1 ML

Simulations

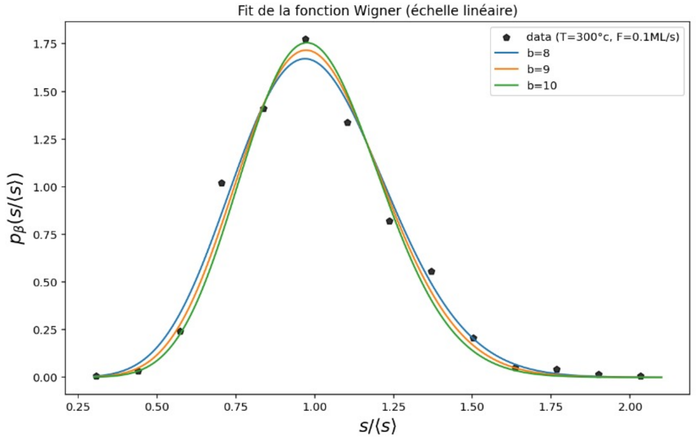


CZD

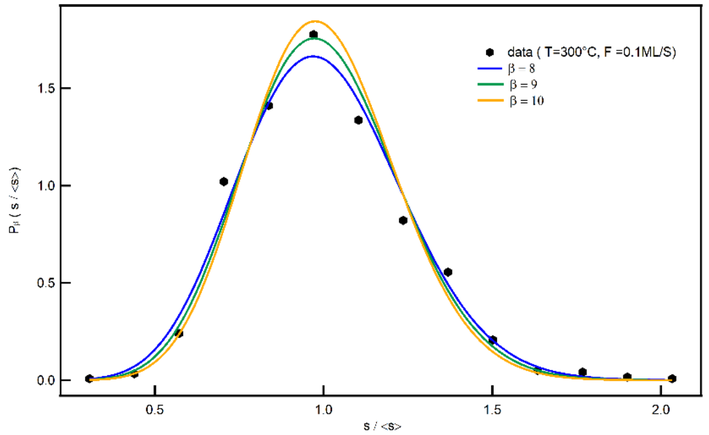


Delaunay triangulation

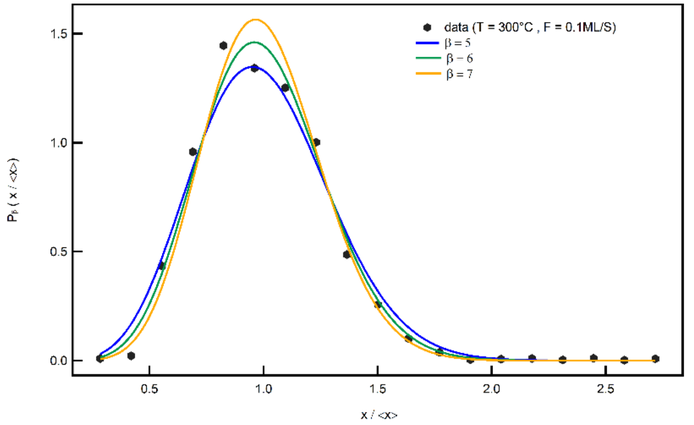
Experiments



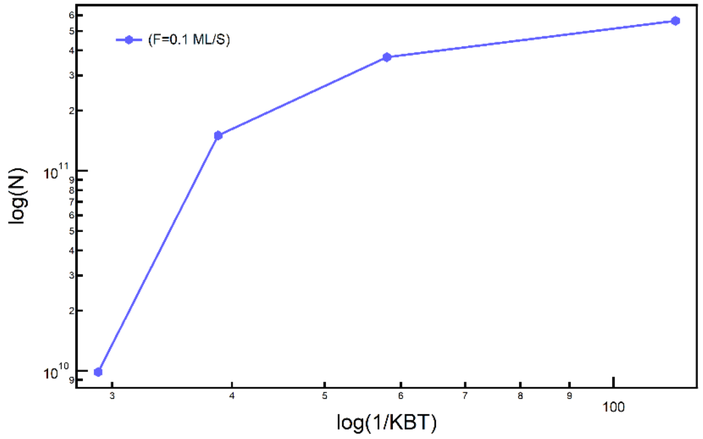
CZD



CZD

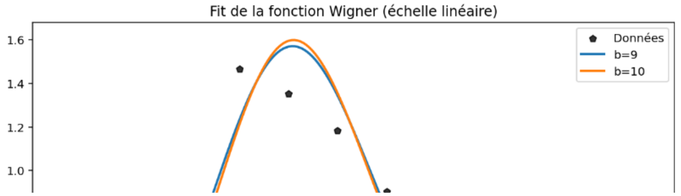


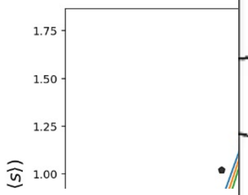
Delaunay triangulation

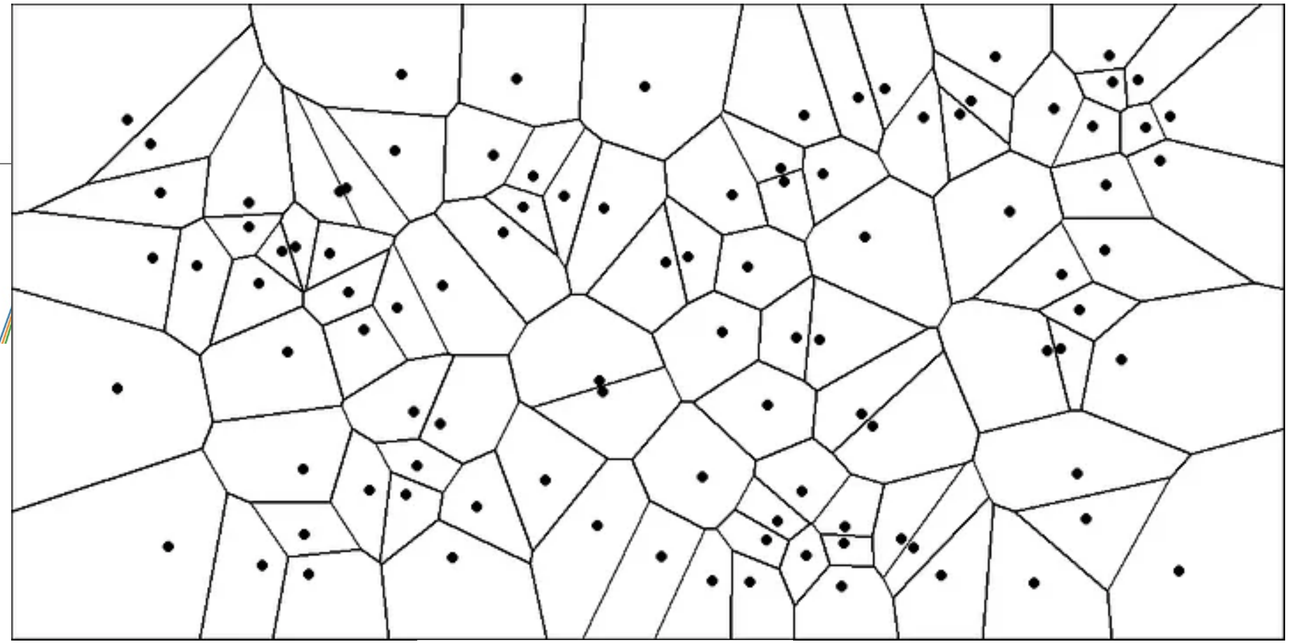


Island density vs. 1/T

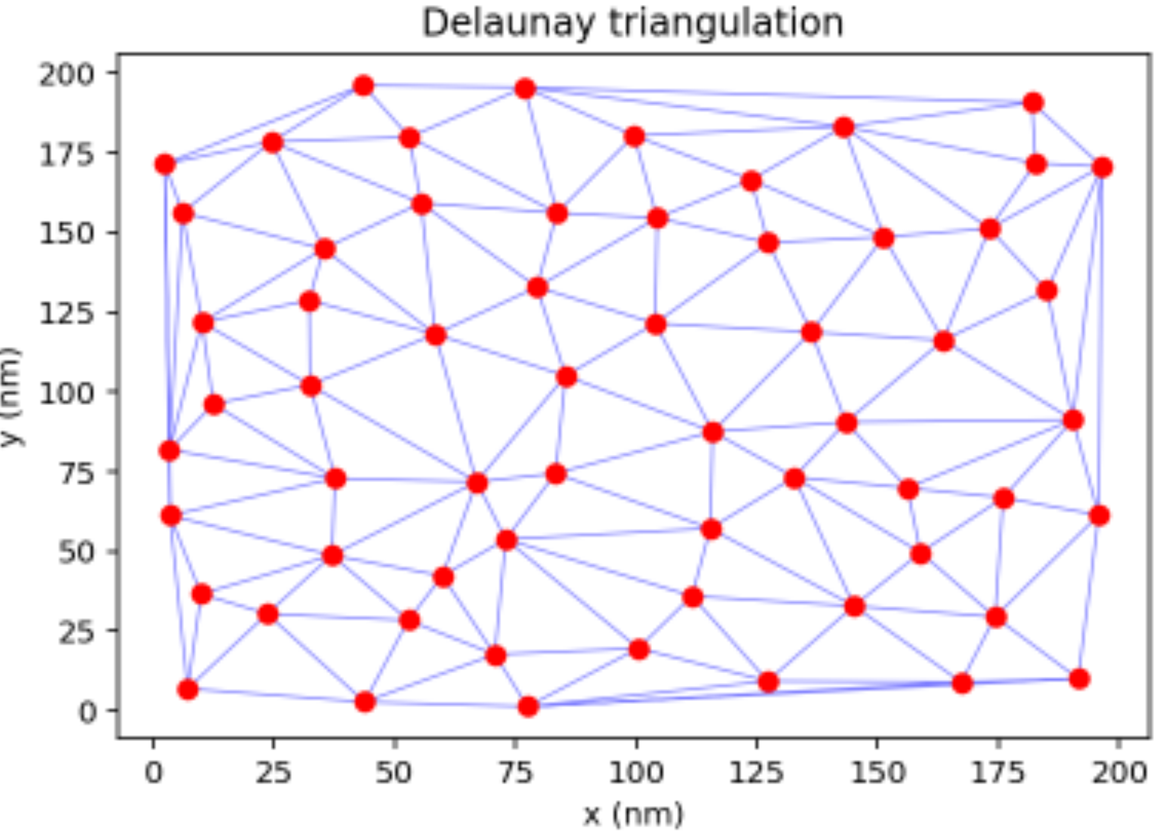
Simulations



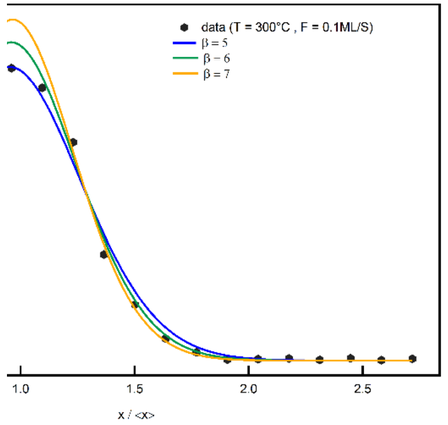




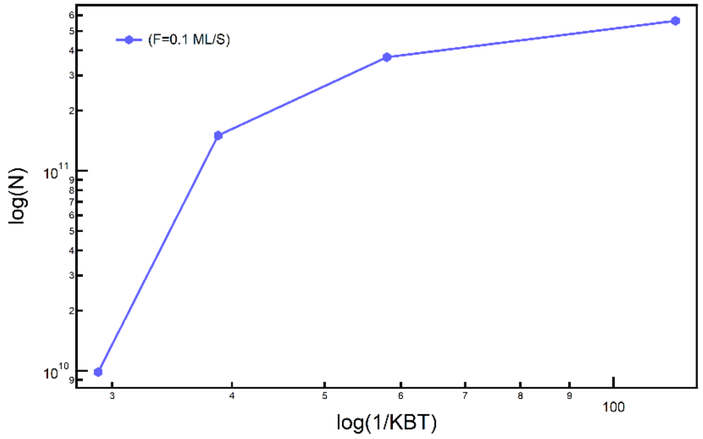
Voronoi polygons



Delaunay triangulation

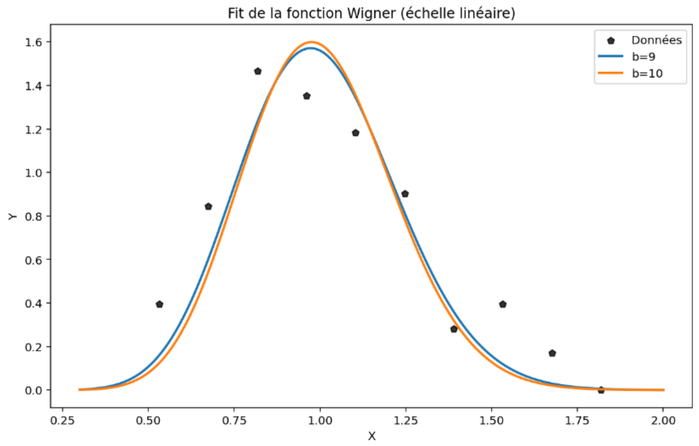


Delaunay triangulation

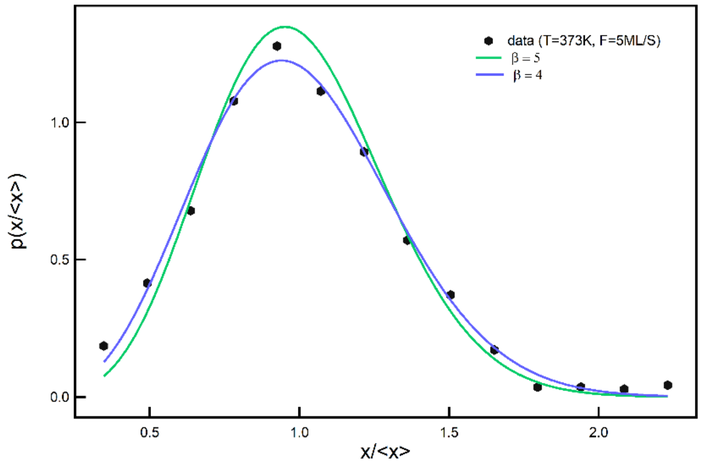


Island density vs. 1/T

Simulations

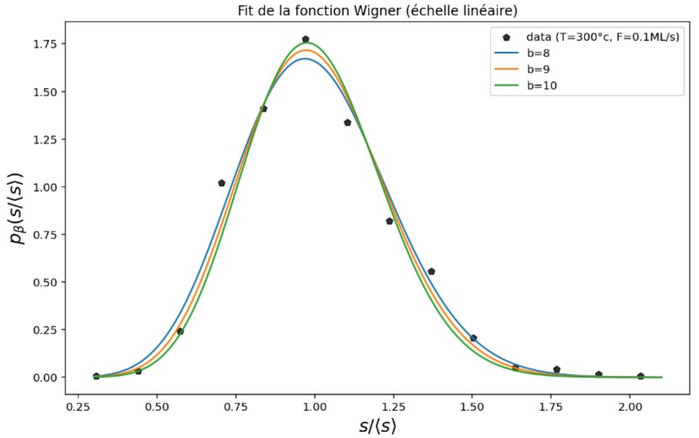


CZD

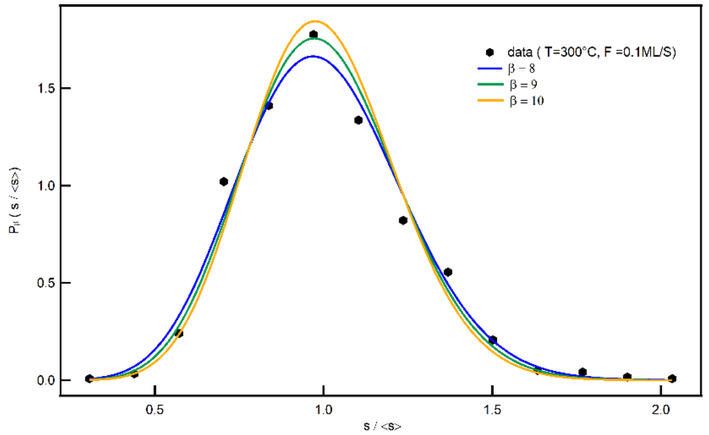


Delaunay triangulation

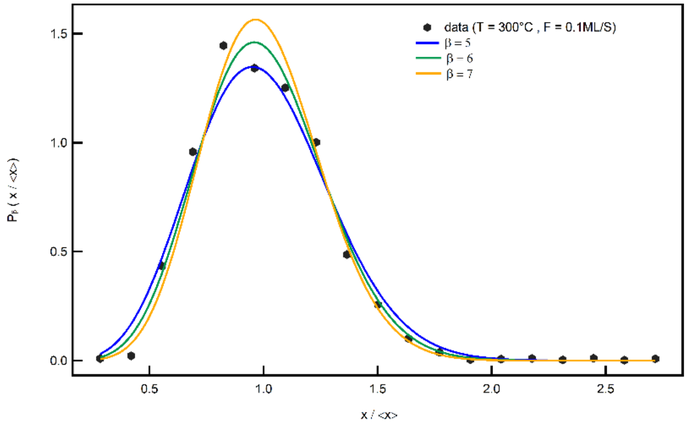
Experiments



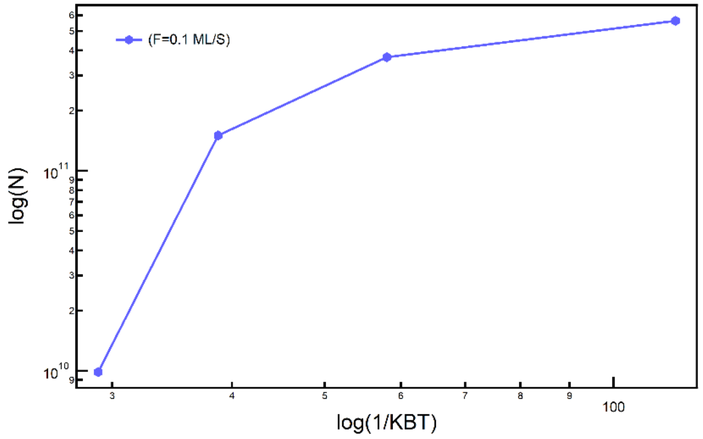
CZD



CZD

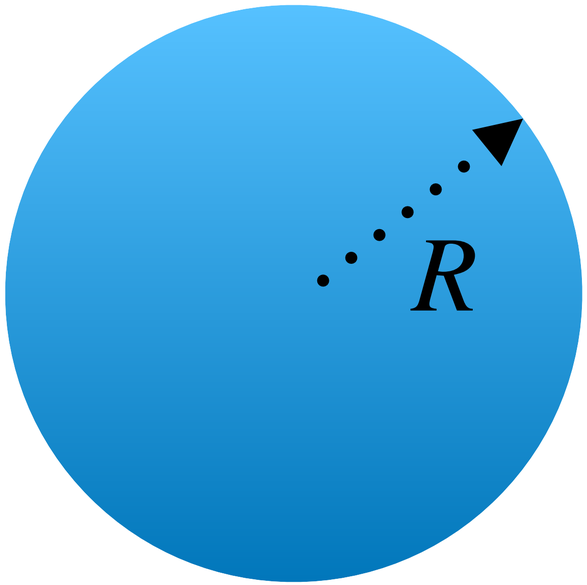


Delaunay triangulation



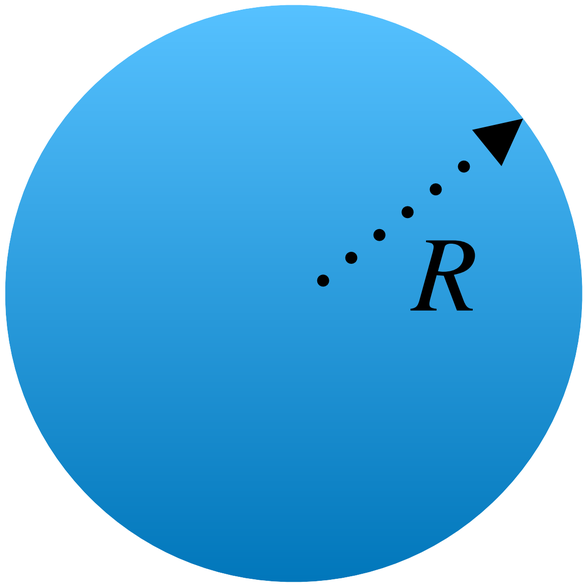
Island density vs. 1/T

Nucleation, Growth, Coarsening: Ostwald Ripening



$$\mu(R) - \mu(\infty) = \Omega \frac{2\sigma}{R}$$

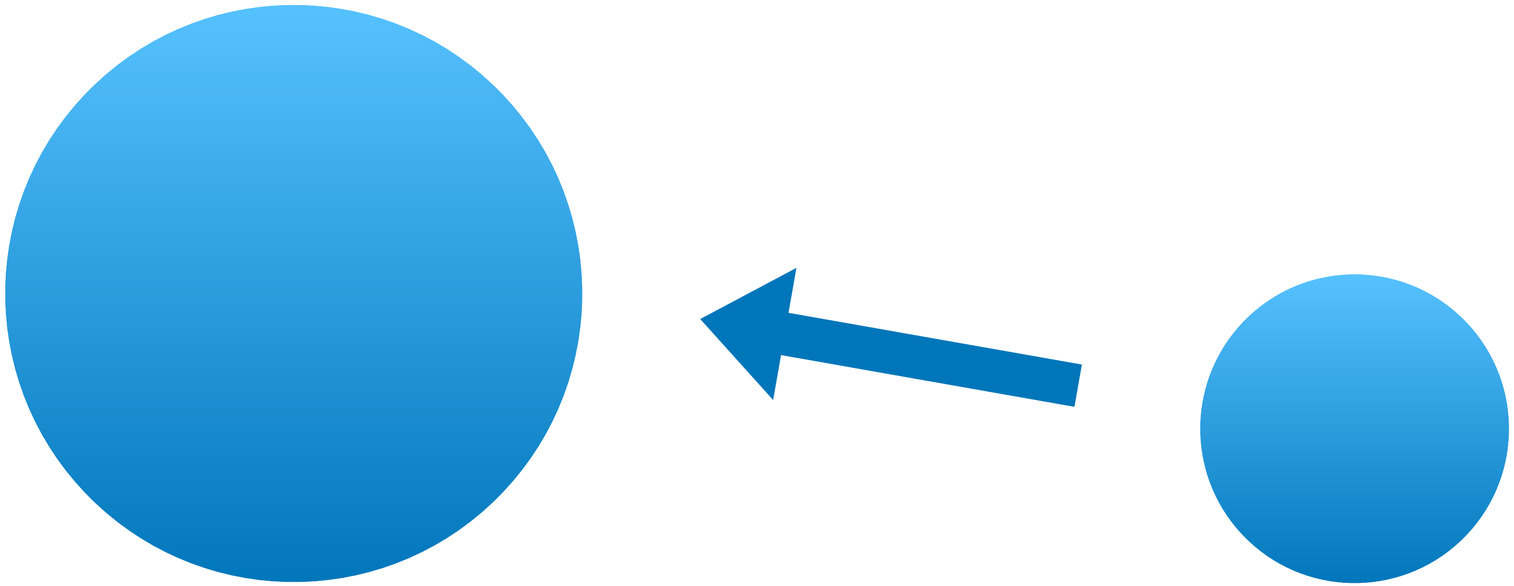
Nucleation, Growth, Coarsening: Ostwald Ripening



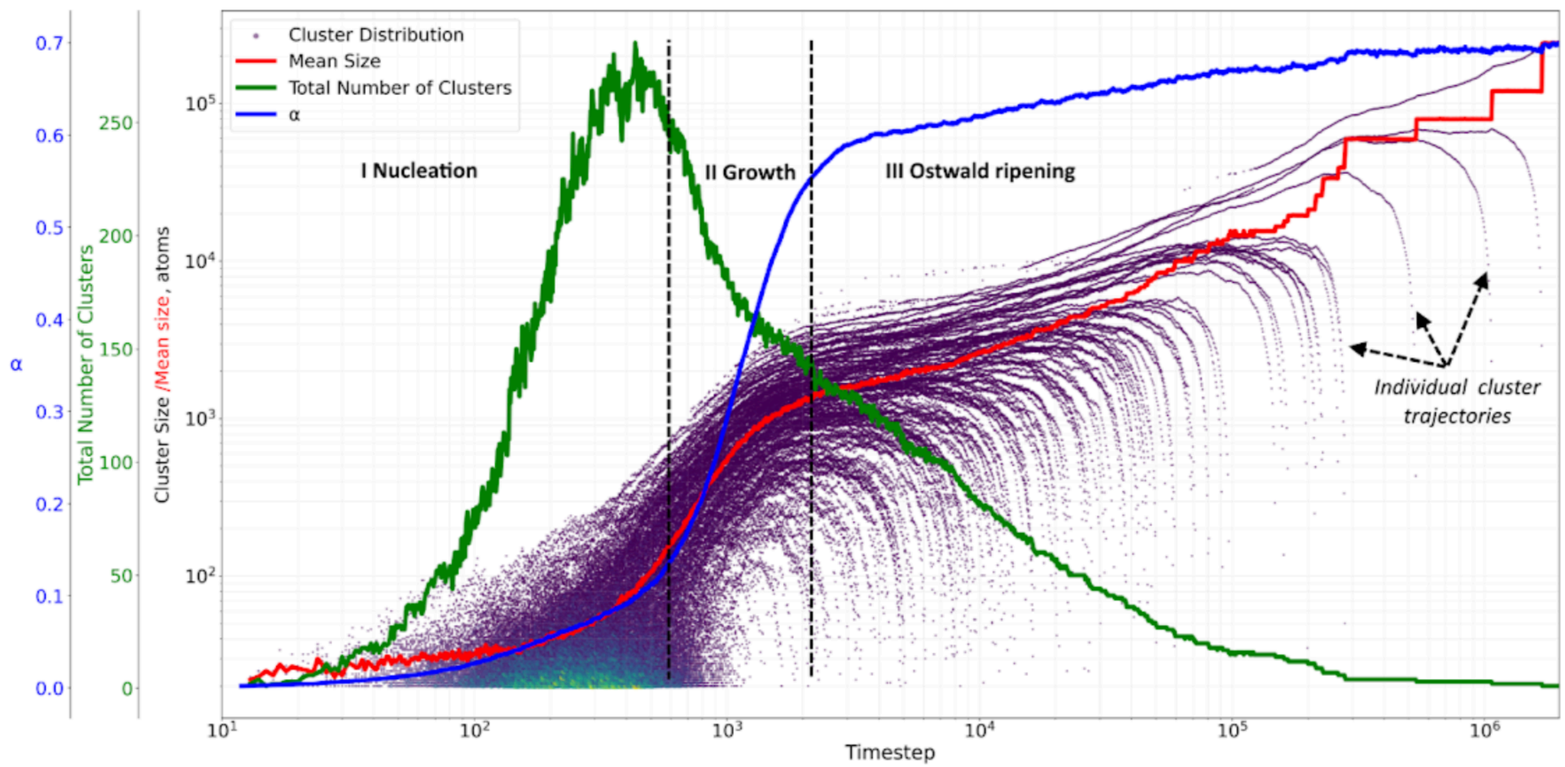
$$c(R) = c(\infty)\exp\left(\Omega\frac{2\sigma}{R}k_BT\right)$$

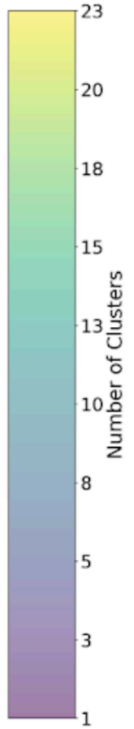
Nucleation, Growth, Coarsening: Ostwald Ripening

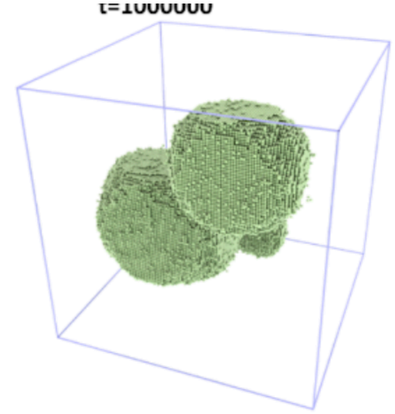
$$\vec{J} = -D\nabla c$$

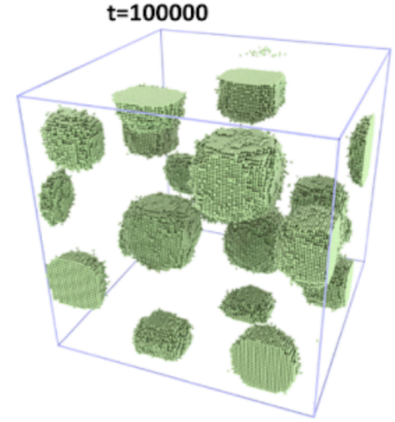


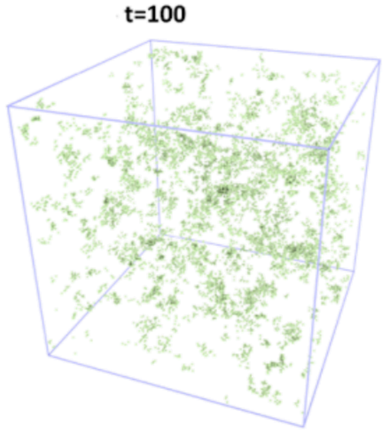
Nucleation, Growth, Coarsening: Ostwald Ripening

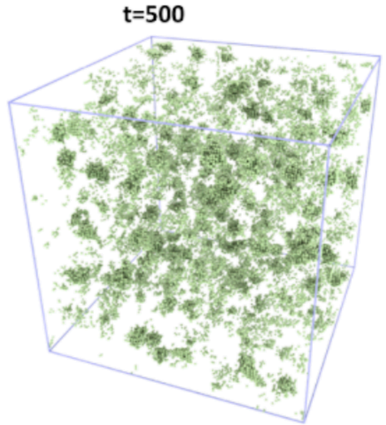


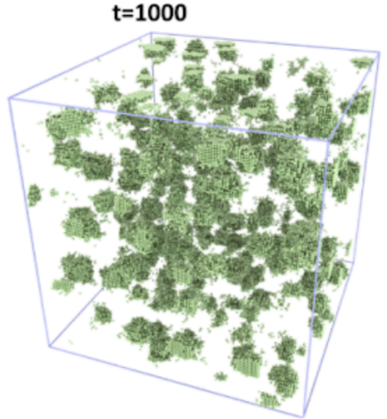


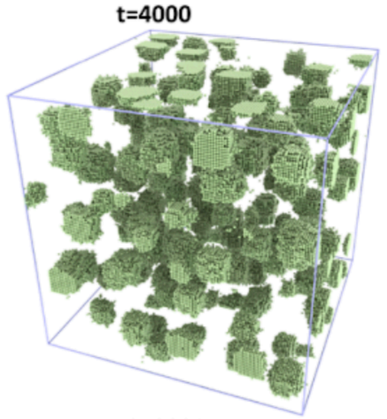


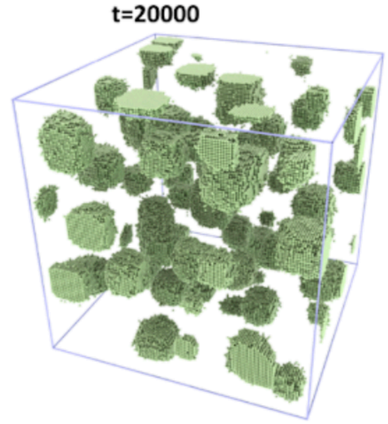












Questions?


YOUR LIFE AMBITION - What Happened??
WORLD, HERE I COME!
Ambition
Win Nobel Prize
Revolutionize your field
Get a job at a top University
Get a job
Attend that Conference in PoDunk, MN
Hope they have Pepperoni Pizza
1st Year
2nd Year
3rd Year
4th Year
5th Year
HAPPY HOUR, HERE I COME!
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Exponent relations (2D islands)

$$P(s) = a_\beta s^\beta \exp(-b_\beta s^2)$$

$$N \sim (F/D)^\alpha$$

$$\beta_{\mathrm{DLA}} = i + 2$$

$$\alpha_{\mathrm{DLA}} = i/(i+2)$$

$$\beta_{\mathrm{ALA}} = (i+3)/2$$

$$\alpha_{\mathrm{ALA}} = 2i/(i+3)$$

Exponent relation

$$P(s) = a_\beta s^\beta \exp(-b_\beta s^2) \qquad N \sim (F/D)^\alpha$$

$$\alpha\beta = i$$

for 2D islands!

Exponent relation

$$P(s) = a_\beta s^\beta \exp(-b_\beta s^2) \qquad N \sim (F/D)^\alpha$$

$$\alpha(2\beta + d - 2) = 2i$$

for d-dimensional islands!

Exponent relation

$$P(s) = a_\beta s^\beta \exp(-b_\beta s^2) \qquad N \sim (F/D)^\alpha$$

$$\alpha(2\beta + 1) = 2i$$

for 3D islands