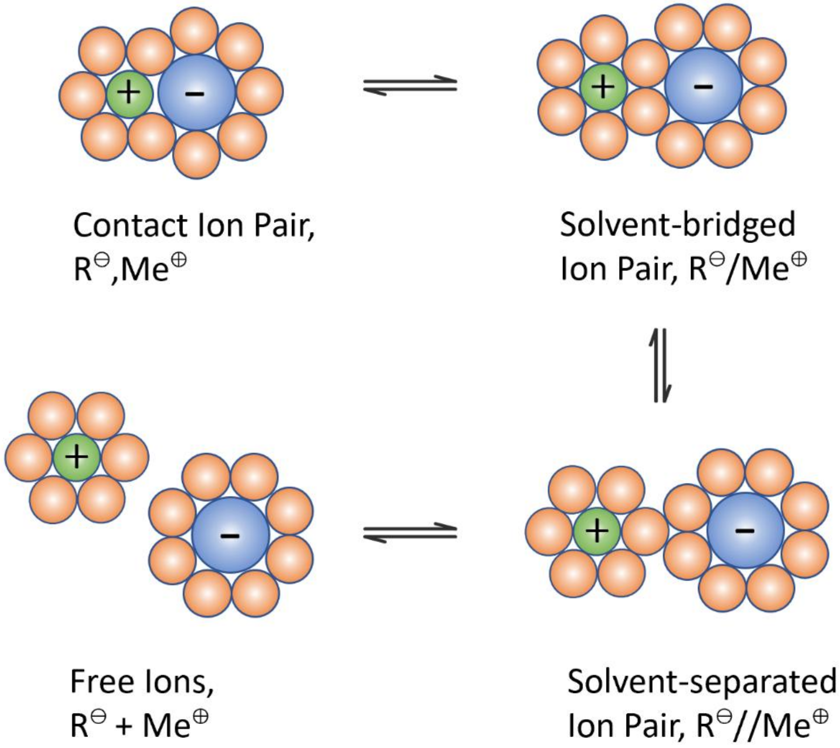
4 – Atomistic aspects of electrocrystallization

I) Solvation of ions

1) Dissolution of a metal salt in polar solvents



Solvent dipoles screen the electrical charge of the ions

Electrical neutrality of the electrolyte is preserved: $\sum_{\alpha} q_{\alpha}\rho_{\alpha} = 0$

with q the charge and ρ the number density

I) Solvation of ions

2) Ion solvation

3 types of interactions:

Ion-ion: $U_{i,j} = \frac{2\pi}{\sum_\alpha \rho_\alpha} \sum_{i,j} q_i q_j \rho_i \rho_j \int_0^\infty g_{i,j}(r) r dr$

Ion-dipole: $U_{i,\mu} = -\frac{4\pi N \rho_\mu \mu}{3 \sum_\alpha \rho_\alpha} \sum_i q_i \rho_i \int_0^\infty g_{i,\mu}(r) dr$

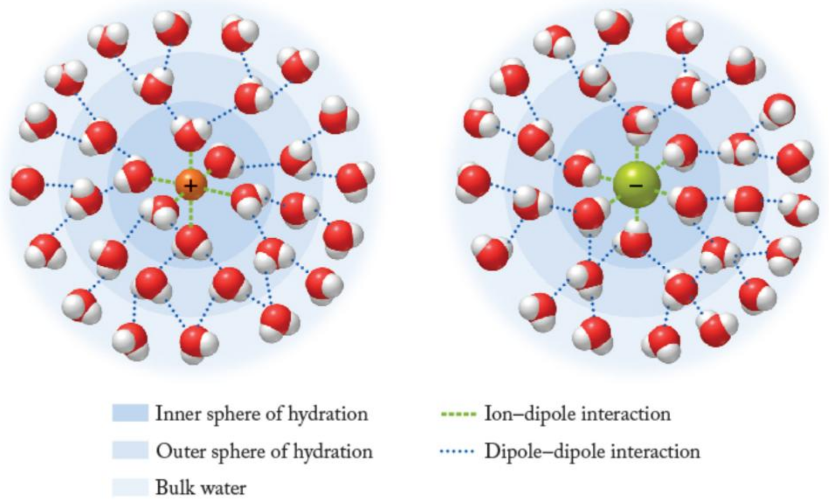
Dipole-dipole: $U_{i,\mu} = -\frac{4\pi N {\rho_\mu}^2 \mu^2}{3 \sum_\alpha \rho_\alpha} \int_0^\infty \frac{g_{\mu,\mu}(r)}{r} dr$

with g(r) the radial distribution function

A hard solvation sphere is formed

→ Metal cations are hydrated

→ Hydration number depends on the Pauling's ionic radius



Octahedral solvation sphere !

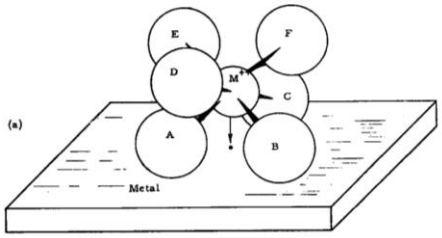
II) Cation-surface interaction

1) Adsorption on a planar surface

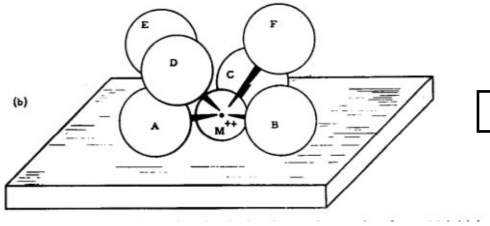
A negative potential is imposed to the substrate

Interaction cathode (-) — cations (+)

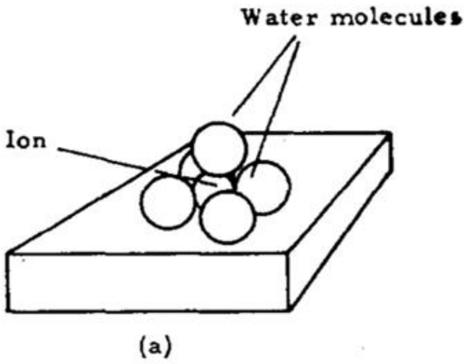
Displacement of the hydration shell and transfer of the cation to the surface



Symmetrical transfer



Cation transfer



Partial dehydration

Symmetrical transfer: only the outer solvation shell is displaced
Need to disrupt the inner shell to transfer the cation to the surface
Loss of one water molecule

II) Cation-surface interaction

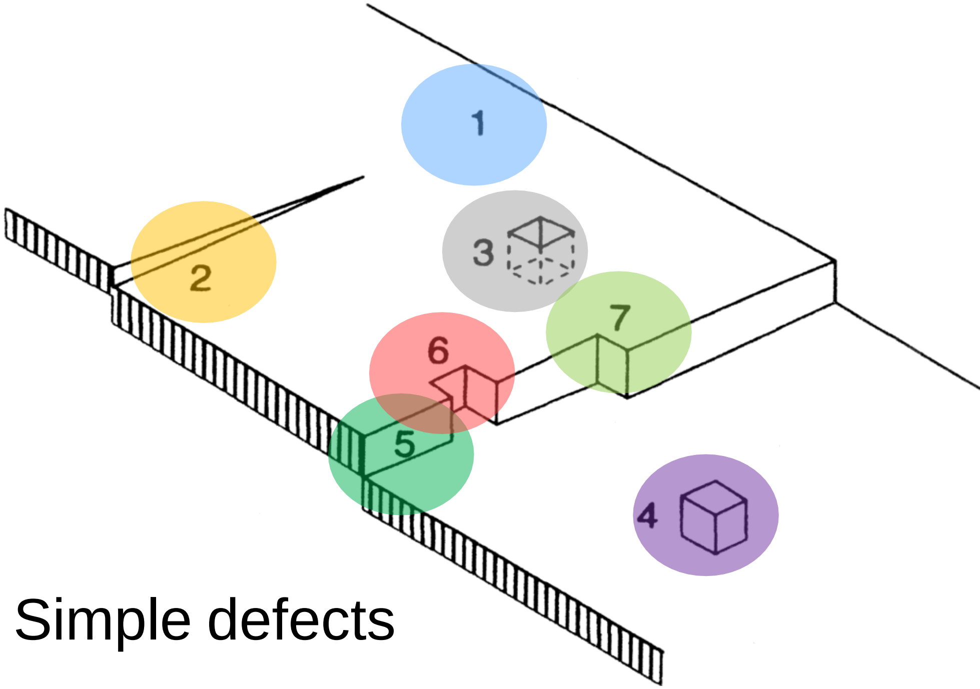
2) Real surfaces

Real surfaces are not ideal surfaces

Density of metal surface atoms 10^{15} cm^{-2}

Density of dislocations $10^{4} – 10^{8}$ cm^{-2}

1. Perfect flat face,terrace
2. Emerging screw dislocation
3. A ledge: monoatomic step
4. Vacancy in the ledge
5. Kink: a ledge in the ledge
6. Vacancy in the terrace
7. Atom on the terrace

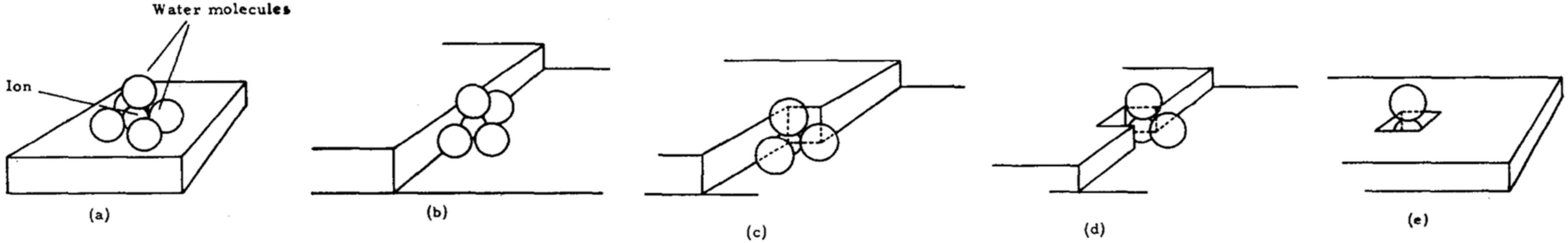


Simple defects

II) Cation-surface interaction

3) Different adsorption sites

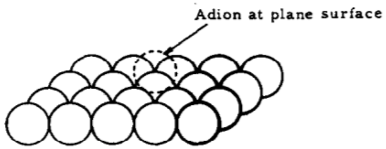
Let us consider the initial state $[M\,(H_2O)_6]^{z+}$ an octahedral metal hydrate



Plane	Ledge	Ledge kink	Ledge vacancy	Plane vacancy
$-\ H_2O$	$-\ 2H_2O$	$-\ 3H_2O$	$-\ 4H_2O$	$-\ 5H_2O$
$[M\,(H_2O)_5]^{z+}$	$[M\,(H_2O)_4]^{z+}$	$[M\,(H_2O)_3]^{z+}$	$[M\,(H_2O)_2]^{z+}$	$[M\,(H_2O)]^{z+}$

II) Cation-surface interaction

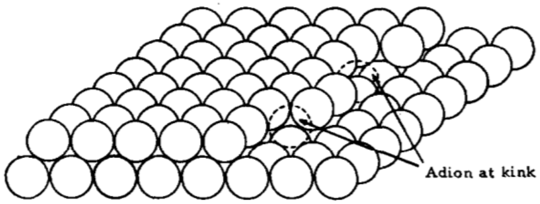
4) Coordination number = neighbouring metal atoms



Adion at a plane surface site: C.N.= 3

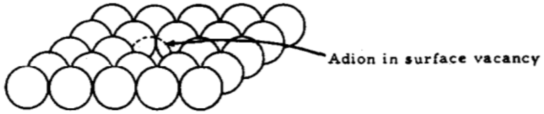
Adion at a monoatomic ledge site: C.N. = 5

Adion at a polyatomic ledge site: C.N. = 6



Adion at kink sites: C.N. = 5 or 6

Adion at edge vacancy sites: C.N. = 7 or 8



Adion at a surface vacancy: C.N. = 9

II) Cation-surface interaction

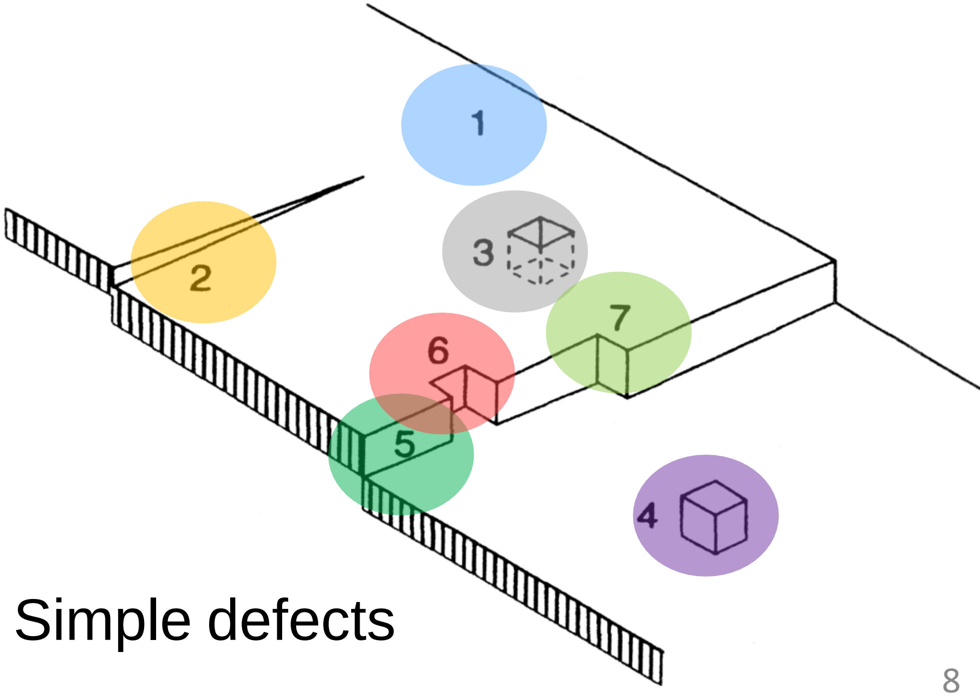
5) Consequence on the electrical activation energy

The electrical activation energy depends on surface site

$$\Delta G^*_{e,3} < \Delta G^*_{e,6} < \Delta G^*_{e,7} \lesssim \Delta G^*_{e,5} \lesssim \Delta G^*_{e,2} < \Delta G^*_{e,4} < \Delta G^*_{e,1}$$

$$C.N.: 9 \quad > 8-7 > 6-5 \geq 6-5 \geq \quad 5 \quad > \quad 4 \quad > \quad 3$$

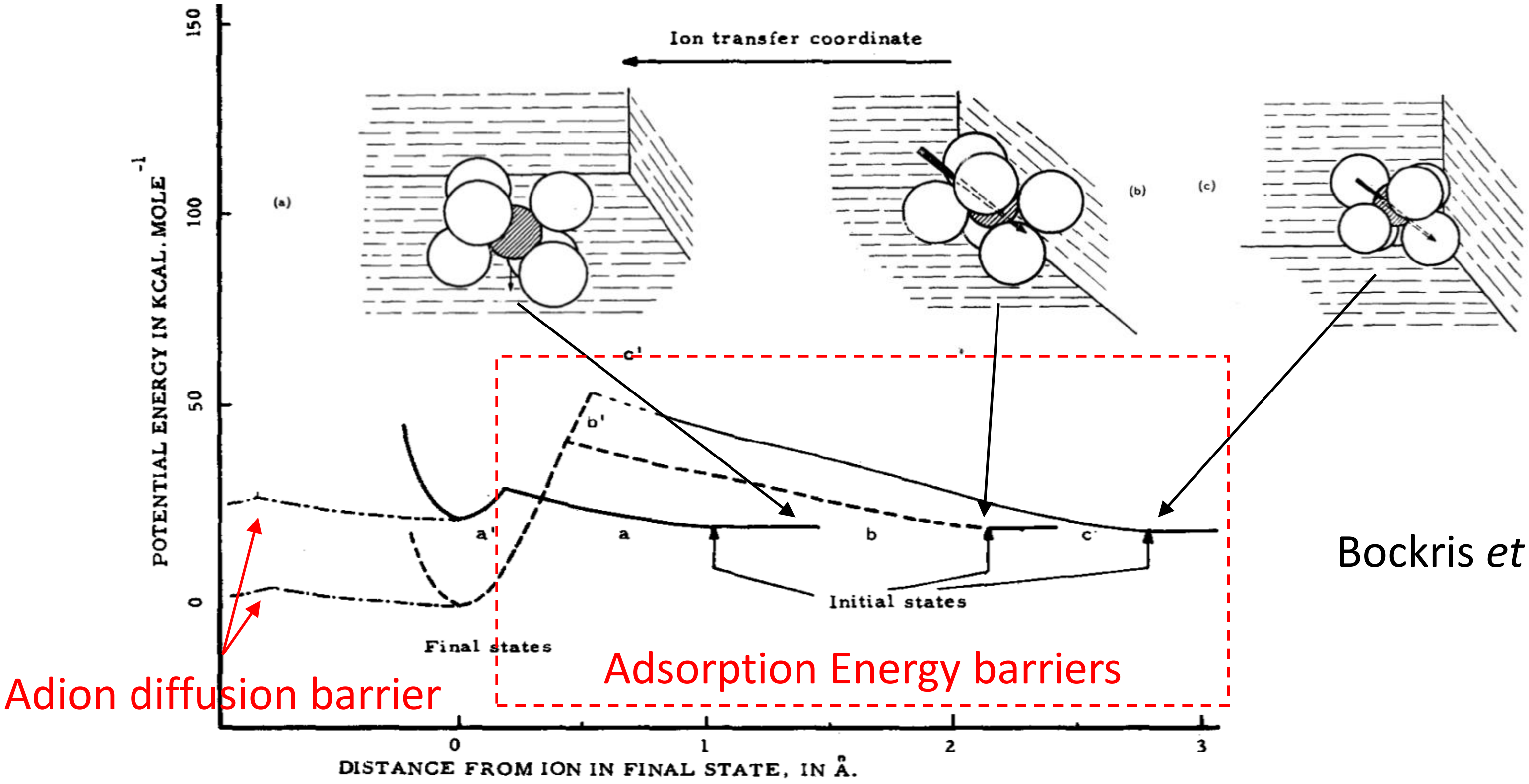
Perfect flat face,terrace
Emerging screw dislocation
Vacancy in the terrace
Adatom in the terrace
A ledge: monoatomic step
Vacancy in the ledge
Kink: a ledge in the ledge



Simple defects

II) Cation-surface interaction

6) Potential energy considerations



Adion diffusion barrier

Adsorption Energy barriers

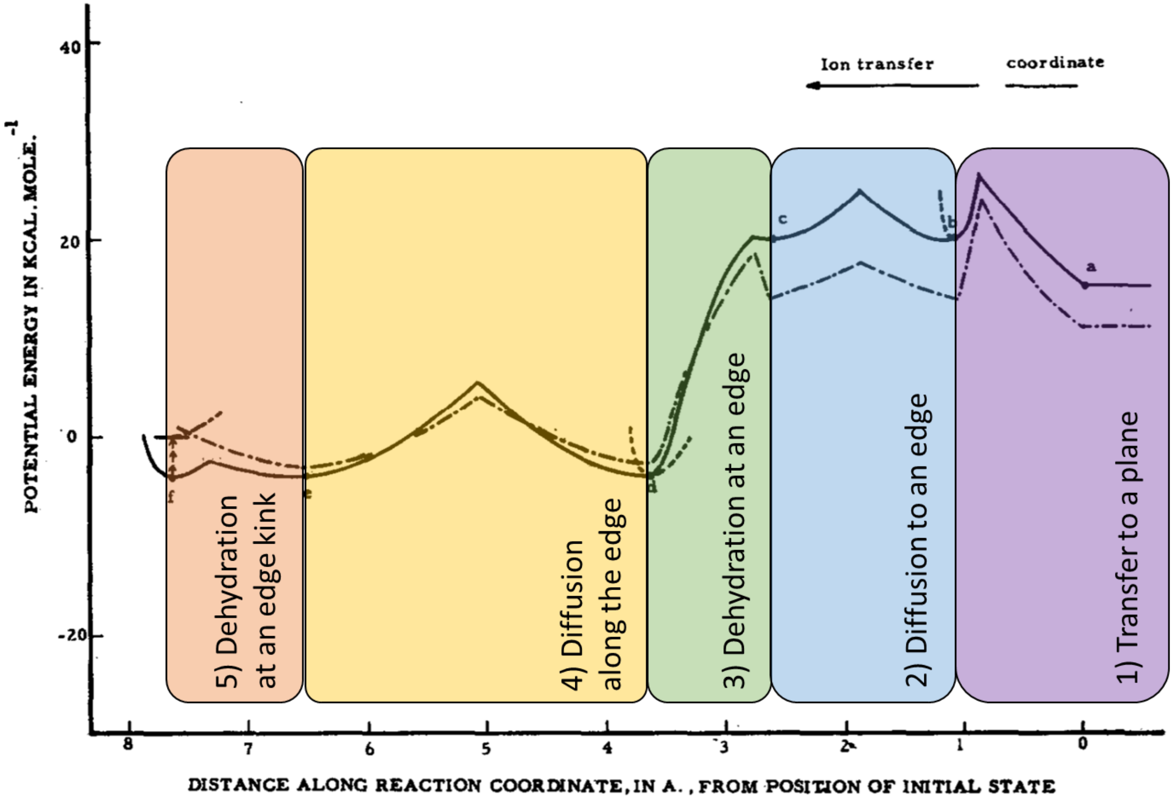
Bockris *et al.*

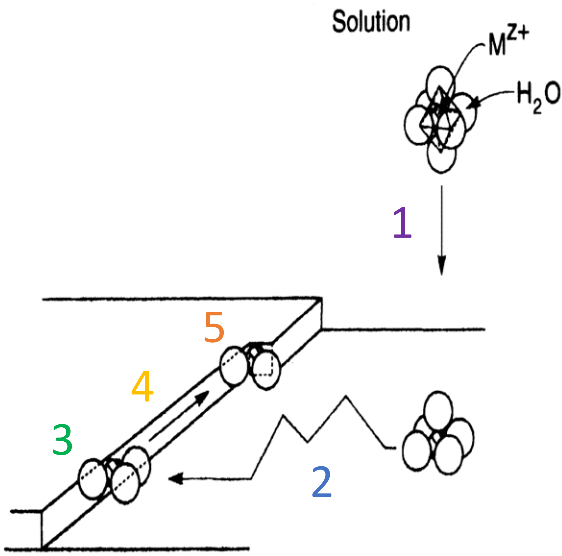
Energy barrier lowest for adsorption on planar surface

Final state most stable at a ledge

II) Cation-surface interaction

7) Most probable pathway





Dashed line = Free energy profile

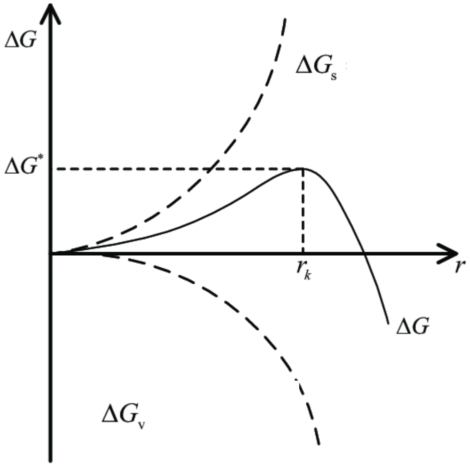
III) Nucleation and growth process

1) Homogeneous nucleation: spherical nucleus

Formation of a monoatomic cluster c_α followed by the progressive addition of N atoms to the cluster: $c_\alpha = c_{\alpha+N}$

Free energy variation during nucleus formation is a function of the number of atoms:

$$\Delta G = \Delta G_{surface} - \Delta G_{volume}$$



III) Nucleation and growth process

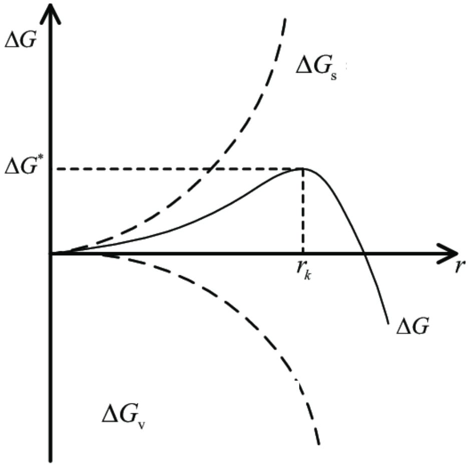
1) Homogeneous nucleation: spherical nucleus

Formation of a monoatomic cluster c_α followed by the progressive addition of N atoms to the cluster: $c_\alpha = c_{\alpha+N}$

Free energy variation during nucleus formation is a function of the number of atoms:

$$\Delta G = \Delta G_{surface} - \Delta G_{volume} = \underbrace{\sigma_s S}_{\neq f(\eta)} - \underbrace{\Delta\mu \frac{V}{V_m}}_{= f(\eta)}$$

σ_s the surface energy, S the surface, $\Delta\mu$ the chemical potential, V and V_m the volume and molar volume



III) Nucleation and growth process

1) Homogeneous nucleation: spherical nucleus

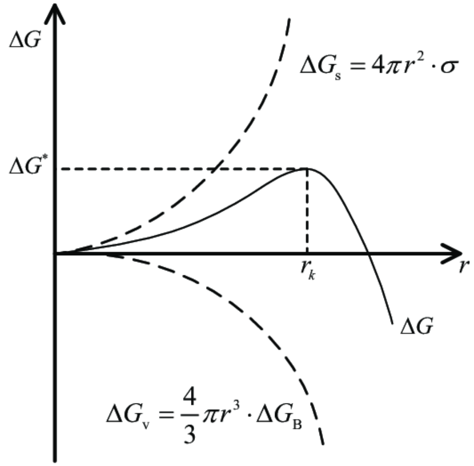
Formation of a monoatomic cluster c_α followed by the progressive addition of N atoms to the cluster: $c_\alpha = c_{\alpha+N}$

Free energy variation during nucleus formation is a function of the number of atoms:

$$\Delta G = \Delta G_{surface} - \Delta G_{volume} = \underbrace{S\sigma_s}_{\neq f(\eta)} - \underbrace{V\frac{\Delta\mu}{V_m}}_{= f(\eta)}$$

σ_s the surface energy, S the surface, $\Delta\mu$ the chemical potential, V and V_m the volume and molar volume

For a spherical nucleus $\Delta G = 4\pi r^2\sigma_s - \frac{4\pi}{3}r^3\frac{\Delta\mu}{V_m}$



III) Nucleation and growth process

1) Homogeneous nucleation: spherical nucleus

Formation of a monoatomic cluster c_α followed by the progressive addition of N atoms to the cluster: $c_\alpha = c_{\alpha+N}$

Free energy variation during nucleus formation is a function of the number of atoms:

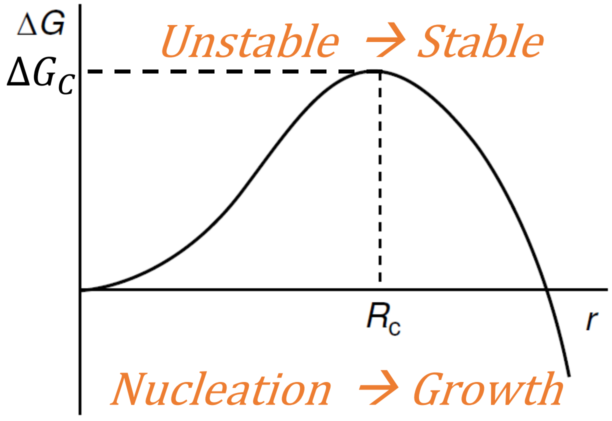
$$\Delta G = \Delta G_{surface} - \Delta G_{volume} = \underbrace{S\sigma_s}_{\neq f(\eta)} - \underbrace{V\frac{\Delta\mu}{V_m}}_{= f(\eta)}$$

σ_s the surface energy, S the surface, $\Delta\mu$ the chemical potential, V and V_m the volume and molar volume

For a spherical nucleus $\Delta G = 4\pi r^2\sigma_s - \frac{4\pi}{3}r^3\frac{\Delta\mu}{V_m}$

Critical nucleus size R_C and V_C: ΔG *is maximum,* $\frac{\partial\Delta G}{\partial r} = 0$

- Differenciation: $\frac{\partial\Delta G}{\partial r} = 8\pi r\sigma_s - 4\pi r^2\frac{\Delta\mu}{V_m}$



Free energy variation vs nucleus radius

III) Nucleation and growth process

1) Homogeneous nucleation: spherical nucleus

Formation of a monoatomic cluster c_α followed by the progressive addition of N atoms to the cluster: $c_\alpha = c_{\alpha+N}$

Free energy variation during nucleus formation is a function of the number of atoms:

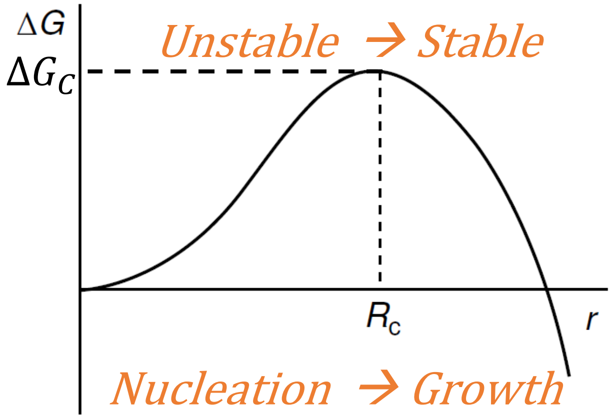
$$\Delta G = \Delta G_{surface} - \Delta G_{volume} = \underbrace{S\sigma_s}_{\neq f(\eta)} - \underbrace{V\frac{\Delta\mu}{V_m}}_{= f(\eta)}$$

σ_s the surface energy, S the surface, $\Delta\mu$ the chemical potential, V and V_m the volume and molar volume

For a spherical nucleus $\Delta G = 4\pi r^2\sigma_s - \frac{4\pi}{3}r^3\frac{\Delta\mu}{V_m}$

Critical nucleus size R_C and V_C: ΔG *is maximum,* $\frac{\partial\Delta G}{\partial r} = 0$

- $\frac{\partial\Delta G}{\partial r} = 8\pi R_C\sigma_s - 4\pi {R_C}^2\frac{\Delta\mu}{V_m} = 0$ $\boxed{\Rightarrow R_C = 2\sigma_s\frac{V_m}{\Delta\mu}}$



Free energy variation vs nucleus radius

III) Nucleation and growth process

1) Homogeneous nucleation: spherical nucleus

Formation of a monoatomic cluster c_α followed by the progressive addition of N atoms to the cluster: $c_\alpha = c_{\alpha+N}$

Free energy variation during nucleus formation is a function of the number of atoms:

$$\Delta G = \Delta G_{surface} - \Delta G_{volume} = \underbrace{S\sigma_s}_{\neq f(\eta)} - \underbrace{V\frac{\Delta\mu}{V_m}}_{= f(\eta)}$$

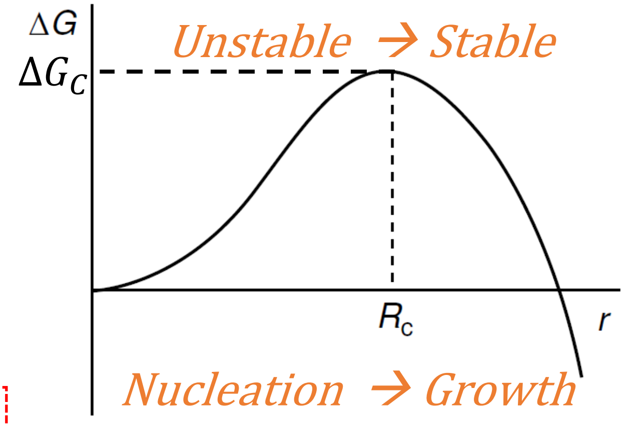
σ_s the surface energy, S the surface, $\Delta\mu$ the chemical potential, V and V_m the volume and molar volume

For a spherical nucleus $\Delta G = 4\pi r^2\sigma_s - \frac{4\pi}{3}r^3\frac{\Delta\mu}{V_m}$

Critical nucleus size R_C and V_C: ΔG *is maximum,* $\frac{\partial\Delta G}{\partial r}=0$

- $\frac{\partial\Delta G}{\partial r} = 8\pi R_C\sigma_s - 4\pi {R_C}^2\frac{\Delta\mu}{V_m} = 0 \Rightarrow R_C = 2\sigma_s\frac{V_m}{\Delta\mu}$

$$\boxed{hence\ \ V_C = \frac{32\pi}{3}\left(\sigma_s\frac{V_m}{\Delta\mu}\right)^3 \ and\ \Delta G_C = \frac{16\pi}{3}{\sigma_s}^3\left(\frac{V_m}{\Delta\mu}\right)^2 = \frac{V_C}{2}\frac{\Delta\mu}{V_m}}$$



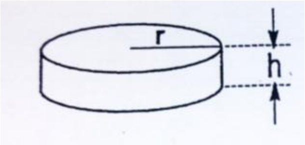
Free energy variation vs nucleus radius

III) Nucleation and growth process

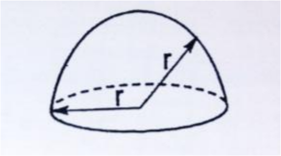
2) Homogeneous nucleation: real nuclei

Expression of the critical volume still holds: $V_C = \Gamma\left(\sigma_S \frac{V_m}{\Delta\mu}\right)^3$

with Γ the shape factor ($\Gamma_{sphere} = \frac{32\pi}{3}, \Gamma_{cube} = 64$)

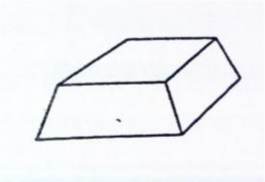


Cylindrical



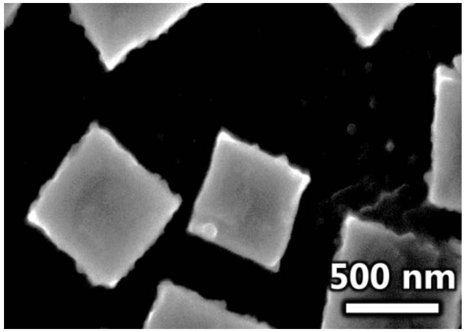
Hemispherical

Conical



Facetted

Anisotropy of the crystal properties
Growth on high surface energy crystal plane is favored

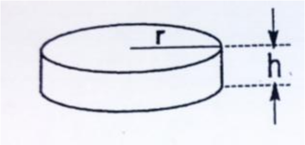


III) Nucleation and growth process

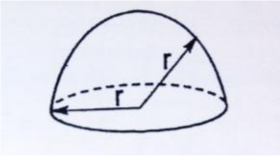
2) Homogeneous nucleation: real nuclei

Expression of the critical volume still holds: $V_C = \Gamma\left(\sigma_s \frac{V_m}{\Delta\mu}\right)^3$

with Γ the shape factor ($\Gamma_{sphere} = \frac{32\pi}{3}, \Gamma_{cube} = 64$)

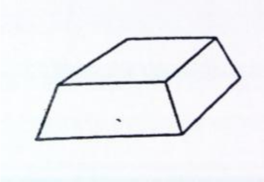


Cylindrical



Hemispherical

Conical



Facetted

More convenient to determine the critical number of atoms n_C than R_C

Let us consider $\nu = \frac{V_m}{\mathcal{N}_A}$ the volume occupied by an atom

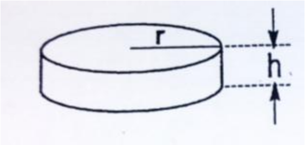
$$n_C = \frac{V_C}{\nu} = \Gamma\left(\frac{\sigma_s \mathcal{N}_A}{\Delta\mu}\right)^3 \upsilon^2 \quad \text{and} \quad \Delta G_C = \frac{V_C}{2}\frac{\Delta\mu}{V_m} = \frac{\Delta\mu}{2\mathcal{N}_A} n_C$$

III) Nucleation and growth process

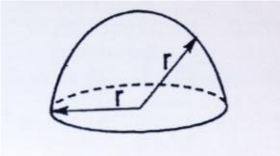
2) Homogeneous nucleation: real nuclei

Expression of the critical volume still holds: $V_C = \Gamma\left(\sigma_s \frac{V_m}{\Delta\mu}\right)^3$

with Γ the shape factor ($\Gamma_{sphere} = \frac{32\pi}{3}, \Gamma_{cube} = 64$)

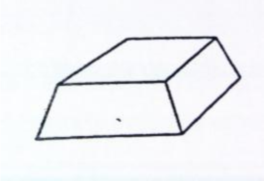


Cylindrical



Hemispherical

Conical



Facetted

More convenient to determine the critical number of atoms n_C than R_C

Let us consider $v = \frac{V_m}{\mathcal{N}_A}$ the volume occupied by an atom

$\Delta\mu$ is related to the overpotential: $\Delta\mu = zF|\eta| = ze\mathcal{N}_A|\eta|$

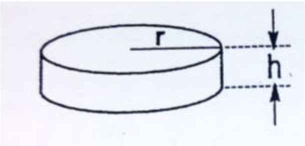
$$n_C = \frac{V_C}{v} = \Gamma\left(\frac{\sigma_s \mathcal{N}_A}{\Delta\mu}\right)^3 v^2 \qquad \text{and} \qquad \Delta G_C = \frac{V_C}{2}\frac{\Delta\mu}{V_m} = \frac{\Delta\mu}{2\mathcal{N}_A} n_C$$

III) Nucleation and growth process

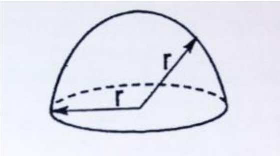
2) Homogeneous nucleation: real nuclei

Expression of the critical volume still holds: $V_C = \Gamma\left(\sigma_s \frac{V_m}{\Delta\mu}\right)^3$

with Γ the shape factor ($\Gamma_{sphere} = \frac{32\pi}{3}, \Gamma_{cube} = 64$)

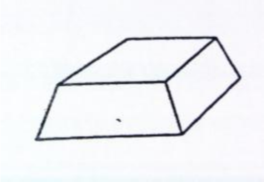


Cylindrical



Hemispherical

Conical



Facetted

More convenient to determine the critical number of atoms n_C than R_C

Let us consider $v = \frac{V_m}{\mathcal{N}_A}$ the volume occupied by an atom

$\Delta\mu$ is related to the overpotential: $\Delta\mu = zF|\eta| = ze\mathcal{N}_A|\eta|$

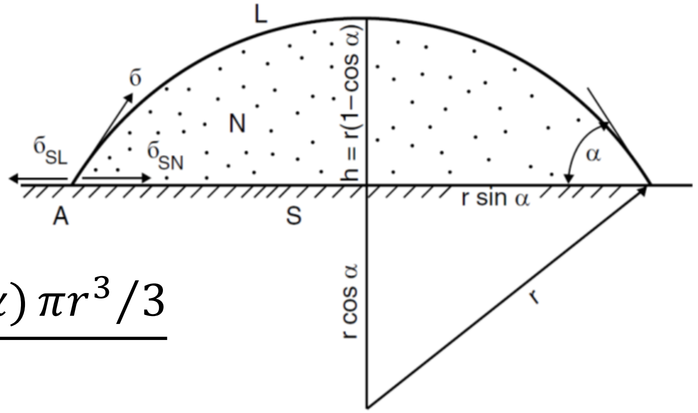
$$n_C = \frac{V_C}{v} = \Gamma\left(\frac{\sigma_s}{ze|\eta|}\right)^3 v^2 \qquad \text{and} \qquad \Delta G_C = \frac{V_C}{2}\frac{\Delta\mu}{V_m} = \frac{ze|\eta|}{2} n_C$$

Increasing the overpotential decreases the critical size of nuclei !!!

III) Nucleation and growth process

3) Heterogeneous 3D nucleation:

Nucleation occurs on a foreign substrate:



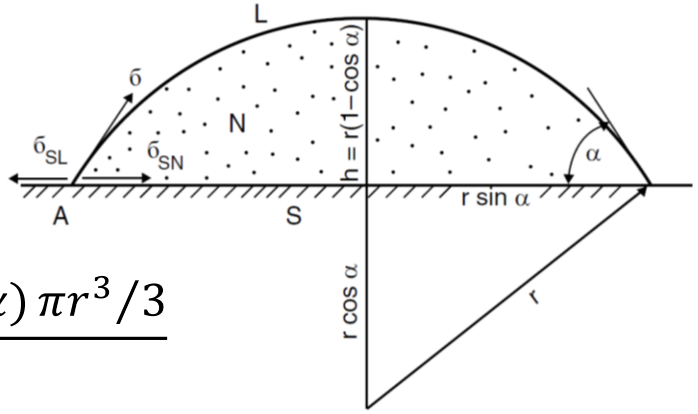
$$\Delta G_C^{het} = \Delta G_C^{hom} \cdot \Theta$$

$$\Theta = \frac{\mathit{Volume\ of\ the\ shell}}{\mathit{Volume\ of\ the\ sphere}} = \frac{(2 - 3\cos\alpha + cos^3\alpha)\,\pi r^3/3}{4\pi r^3/3}$$

III) Nucleation and growth process

3) Heterogeneous 3D nucleation:

Nucleation occurs on a foreign substrate:



$$\Delta G_C^{het} = \Delta G_C^{hom} \cdot \Theta$$

$$\Theta = \frac{Volume\ of\ the\ shell}{Volume\ of\ the\ sphere} = \frac{(2 - 3\cos\alpha + cos^3\alpha)\,\pi r^3/3}{4\pi r^3/3}$$

The contact angle is related to the surface energies via the Young equation:

Surface Adhesion

$$\Theta = \frac{2\sigma_s - \sigma_{Ad}}{2\sigma_s} = \frac{\Delta\sigma}{2\sigma_s} < 1$$

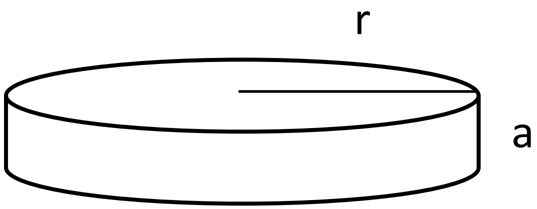
$n_C = \frac{V_C}{\nu} = \frac{16\pi}{3}\frac{{\sigma_s}^2\Delta\sigma}{(ze|\eta|)^3}\nu^2$ and $\Delta {G_C}^{3D} = \frac{ze|\eta|}{2}n_C$

Stronger adhesion decreases the critical size of nuclei !!!

III) Nucleation and growth process

4) Heterogeneous 2D nucleation:

Nucleation occurs on a foreign substrate (only a few atoms thick):



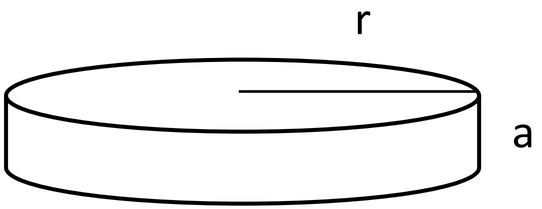
$$\Delta G = \qquad \sigma_s S \qquad - \quad \Delta\mu \frac{V}{V_m}$$

$$\Delta G = \{\pi r^2 \Delta\sigma + 2\pi r a \sigma_s\} - \left\{ zF\eta \frac{\pi r^2 a}{V_m} \right\}$$

III) Nucleation and growth process

4) Heterogeneous 2D nucleation:

Nucleation occurs on a foreign substrate (only a few atoms thick):



$$\Delta G = \qquad \sigma_s S \qquad - \quad \Delta\mu \frac{V}{V_m}$$

$$\Delta G = \{\pi r^2 \Delta\sigma + 2\pi r a \sigma_s\} - \left\{zF\eta \frac{\pi r^2 a}{V_m}\right\}$$

$$r_c = \frac{V_m a \sigma_s}{zF|\eta|a - V_m \Delta\sigma} \text{ and } \qquad \Delta G_C{}^{2D} = \frac{\pi \sigma_s{}^2 \nu a^2}{ze|\eta|a - \nu\Delta\sigma}$$

The critical size of nuclei decreases for higher overpotential and stronger adhesion !!!

III) Nucleation and growth process

5) Nucleation mechanism:

Weak adhesion: $\Delta\sigma > 0$ $\sigma_{Ad} < 2\sigma_s$

$$\Delta G_C{}^{2D} = \Delta G_C{}^{3D} \quad \Leftrightarrow \quad \frac{\pi \sigma_s{}^2 \nu a^2}{ze\eta a - \nu\Delta\sigma} = \frac{8\pi}{3} \frac{\sigma_s{}^2 \Delta\sigma}{(ze\eta)^2} \nu^2$$

$$\eta_{3D \mapsto 2D} = \frac{2\Delta\sigma}{azF}$$

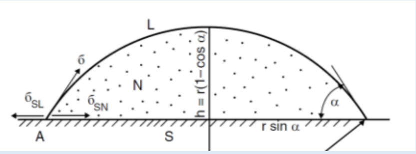
III) Nucleation and growth process

5) Nucleation mechanism:

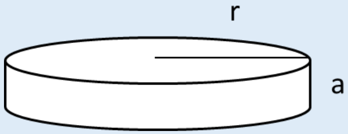
Weak adhesion: $\Delta\sigma > 0$

$\sigma_{Ad} < 2\sigma_s$

$\Rightarrow\ 0 < \eta < \frac{2\Delta\sigma}{azF}$ $\Rrightarrow$ 3D nucleation process



$\Rightarrow\ \eta \geq \frac{2\Delta\sigma}{azF}$ $\Rrightarrow$ 2D nucleation process



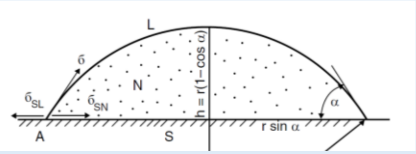
III) Nucleation and growth process

5) Nucleation mechanism:

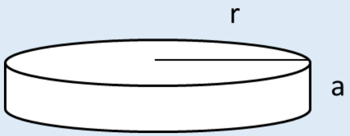
Weak adhesion: $\Delta\sigma > 0$

$\sigma_{Ad} < 2\sigma_s$

$\Rightarrow\ 0 < \eta < \frac{2\Delta\sigma}{azF}$ $\Rrightarrow$ 3D nucleation process



$\Rightarrow\ \eta \geq \frac{2\Delta\sigma}{azF}$ $\Rrightarrow$ 2D nucleation process

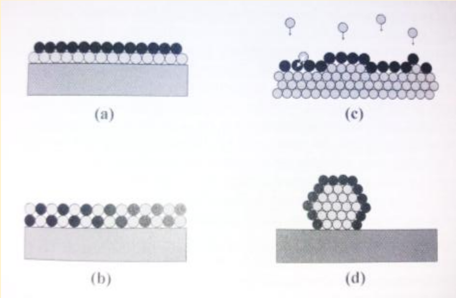


Strong adhesion: $\Delta\sigma < 0$

$\sigma_{Ad} > 2\sigma_s$

$\Rightarrow \frac{\Delta\sigma}{azF} < \eta < 0$ $\Rrightarrow$ 2D nucleation can occur above E_{eq}

Underpotential Deposition (UPD)



Limited to 1 or 2 monolayers

Enables electrochemical atomic layer epitaxy (ECALE)

III) Nucleation and growth process

6) Growth of single nucleus

The growth rate normal to a surface $\mathrm{R(t)} = \frac{iV_m t}{zF}$ *(from Faraday law)*

Hemispherical 3D cluster

$$Show\ that\ I(t) = f(t^2)$$

Cylindrical 2D cluster

$$Show\ that\ I(t) = f(t)$$

III) Nucleation and growth process

6) Growth of single nucleus

The growth rate normal to a surface $\mathrm{R(t)} = \frac{iV_m t}{zF}$

Hemispherical 3D cluster

$I(t) = 2\pi R(t)^2 i$ with the hemisphere radius: $R(t) = \frac{iV_m t}{zF}$

thus $I(t) = 2\pi \left(\frac{V_m t}{zF}\right)^2 i^3 = f(t^2)$

Cylindrical 2D cluster

$I(t) = 2\pi a R(t) i$ with the cylinder radius: $R(t) = \frac{iV_m t}{zF}$

thus $I(t) = 2\pi \frac{V_m t}{zF} i^2 = f(t)$

III) Nucleation and growth process

7) Nucleation kinetics

Nucleation law:

There exists a uniform probability that a surface site is converted into a nucleus
A surface has only a limited number of available nucleation sites N_0

The number of sites N(t) occupied at time t follows a linear kinetics:

$$N(t) = N_0(1 - exp^{-k_n t})$$

where k_n is the nucleation constant

III) Nucleation and growth process

7) Nucleation kinetics

Nucleation law:

There exist a uniform probably that a surface site is converted into a nucleus
A surface has only a limited number of available nucleation sites N_0

The number of sites N(t) occupied at time t follows a linear kinetics:

$$N(t) = N_0(1 - exp^{-k_n t})$$

where the nucleation constant k_n strongly depends on i/η

$$k_n \ is \ large \ \Longrightarrow fast \ nucleation \Longrightarrow N(t = \tau) = N_0$$

Instantaneous nucleation: all sites are occupied in a short induction time τ

$$k_n \ is \ small \Longrightarrow slow \ nucleation \Longrightarrow N(t) = N_0 k_n t$$

Progressive nucleation: site occupation is linear with time

III) Nucleation and growth process

8) Nucleation models

$N(t = \tau) = N_0$

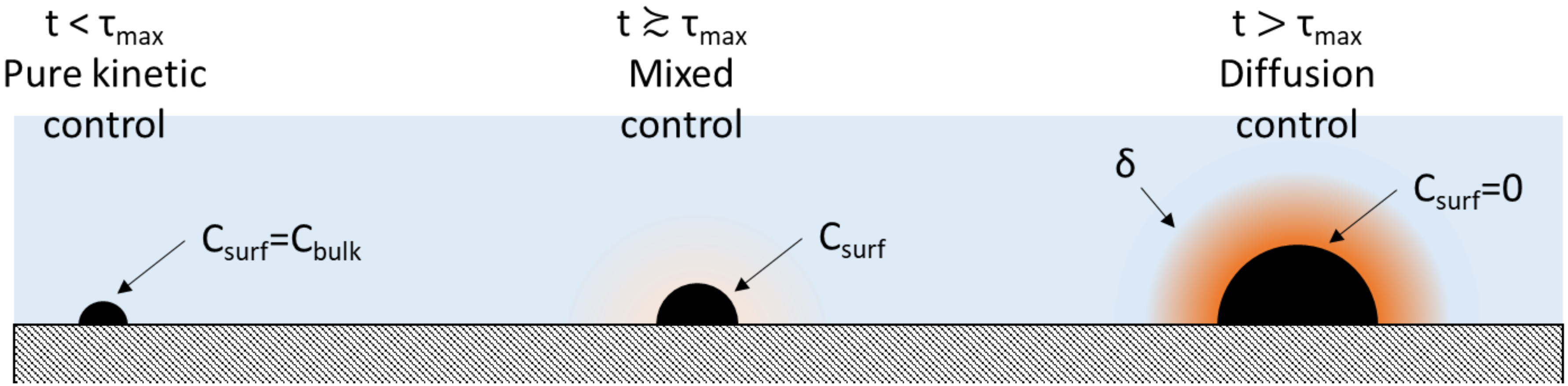
$N(t) = N_0 k_n t$

	Instantaneous	Progressive
3D	$i(t) = 2\pi N_0 \left(\frac{V_m}{zF}\right)^2 i^3 \cdot \boldsymbol{t^2}$	$i(t) = 2\pi N_0 k_n \left(\frac{V_m}{zF}\right)^2 i^3 \cdot \boldsymbol{t^3}$
2D	$i(t) = 2\pi N_0 \frac{V_m}{zF} i^2 \cdot \boldsymbol{t}$	$i(t) = 2\pi N_0 k_n \frac{V_m}{zF} i^2 \cdot \boldsymbol{t^2}$

$t < t_{max}$: no mass transfer limitation, no overlapping

III) Nucleation and growth process

9) Nucleation and growth models



$t < \tau_{max}$
Pure kinetic control

$C_{surf}=C_{bulk}$

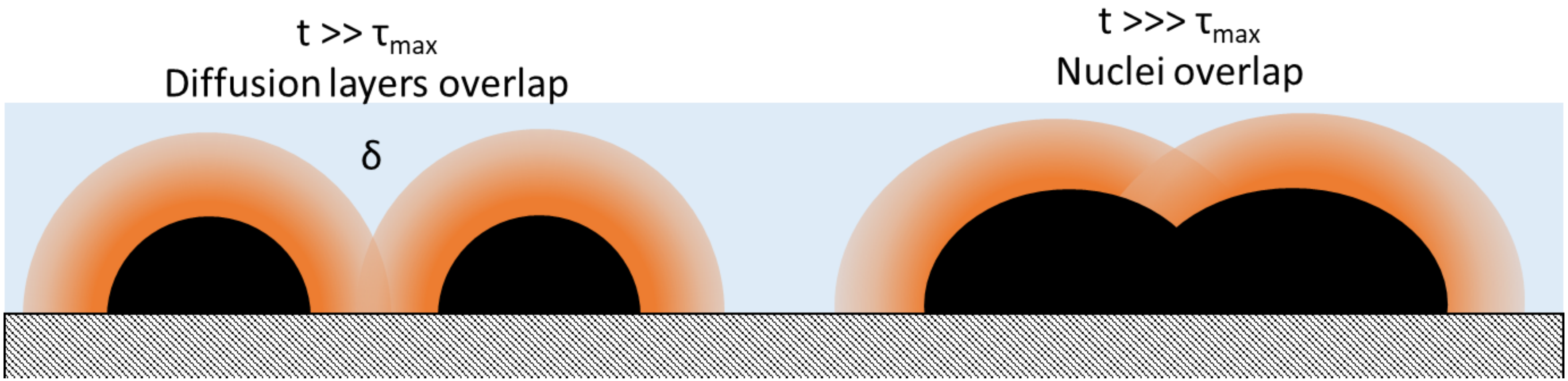
$t \gtrsim \tau_{max}$
Mixed control

C_{surf}

$t > \tau_{max}$
Diffusion control

δ

$C_{surf}=0$



$t >> \tau_{max}$
Diffusion layers overlap

δ

$t >>> \tau_{max}$
Nuclei overlap

III) Nucleation and growth process

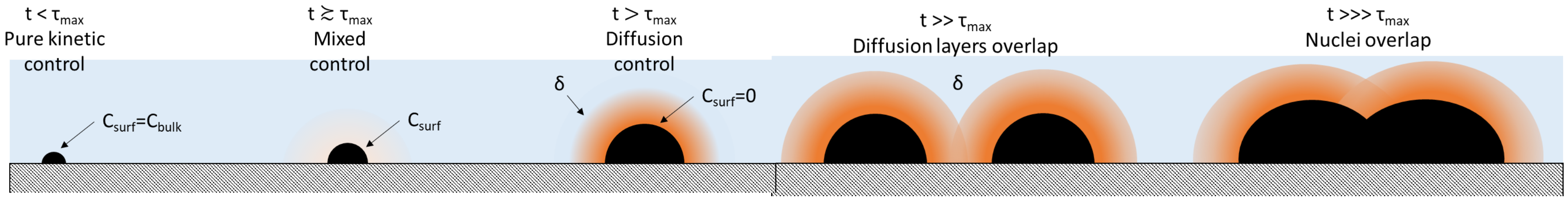
9) Nucleation and growth models

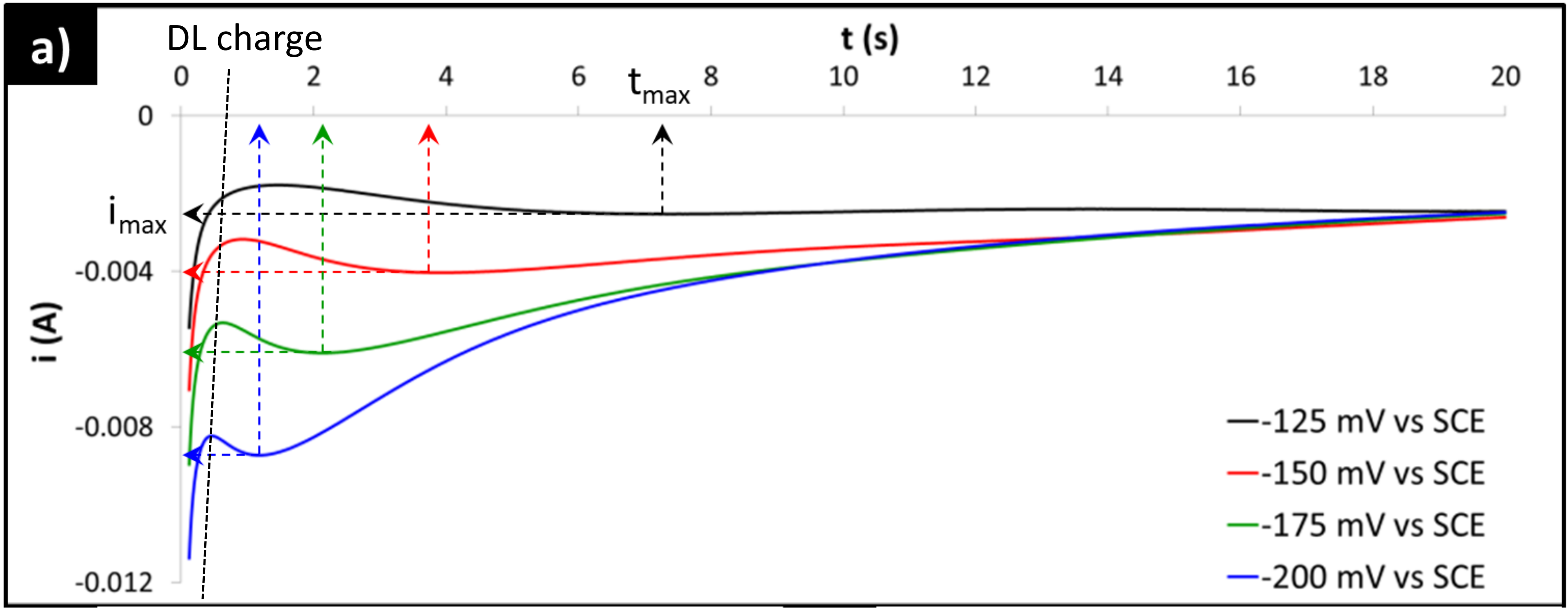
Accounting for overlapping: *Bewick, Scharifker and Hills (1962, 1983)*

	Instantaneous	Progressive
3D	$i(t) = 2\pi N_0 \left(\frac{V_m}{zF}\right)^2 i^3 \cdot \mathbf{t^2} \cdot exp^{-\pi V_m^2 N_0 k_n^2 \mathbf{t^2}}$	$i(t) = 2\pi N_0 k_n \left(\frac{V_m}{zF}\right)^2 i^3 \cdot \mathbf{t^3} \cdot exp^{-\frac{\pi V_m^2 N_0 k_n^2 \mathbf{t^3}}{3}}$
2D	$i(t) = 2\pi N_0 \frac{V_m}{zF} i^2 \cdot \mathbf{t} \cdot exp^{-\pi V_m^2 N_0 k_n^2 \mathbf{t^2}}$	$i(t) = 2\pi N_0 k_n \frac{V_m}{zF} i^2 \cdot \mathbf{t^2} \cdot exp^{-\frac{\pi V_m^2 N_0 k_n^2 \mathbf{t^3}}{3}}$

III) Nucleation and growth process

9) Nucleation and growth models





III) Nucleation and growth process

9) Nucleation and growth models

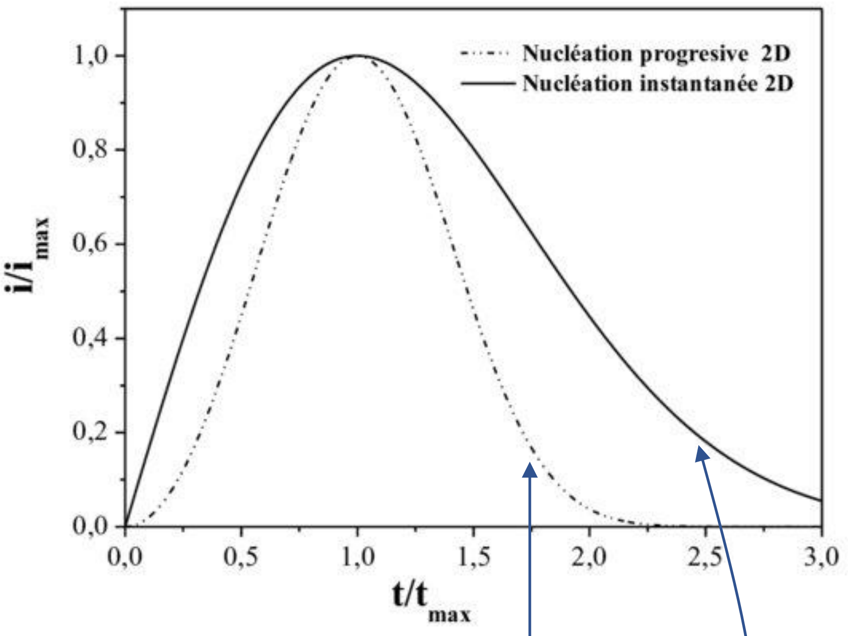
Accounting for overlapping: *Bewick, Scharifker and Hills (1962, 1983)*

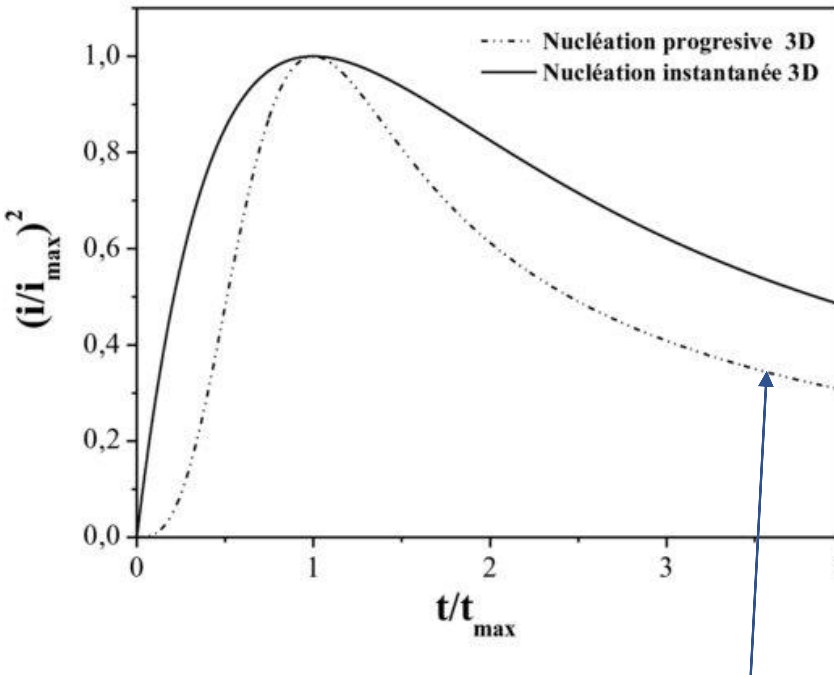
	Instantaneous	Progressive
3D	$\left(\frac{i}{i_{max}}\right)^2 = 1.9542\left(\frac{t_{max}}{t}\right)\left[1 - exp^{-1.2564\left(\frac{t}{t_{max}}\right)}\right]^2$	$\left(\frac{i}{i_{max}}\right)^2 = 1.2254\left(\frac{t_{max}}{t}\right)\left[1 - exp^{-2.3367\left(\frac{t}{t_{max}}\right)^2}\right]^2$
2D	$\left(\frac{i}{i_{max}}\right) = \left(\frac{t}{t_{max}}\right) e^{\left[\frac{1}{2} - \frac{1}{2}\left(\frac{t}{t_{max}}\right)^2\right]}$	$\left(\frac{i}{i_{max}}\right) = \left(\frac{t}{t_{max}}\right)^2 e^{\left[\frac{2}{3} - \frac{2}{3}\left(\frac{t}{t_{max}}\right)^3\right]}$

III) Nucleation and growth process

9) Nucleation and growth models

Accounting for overlapping: *Bewick, Scharifker and Hills (1962, 1983)*





$$\left(\frac{i}{i_{max}}\right) = \left(\frac{t}{t_{max}}\right)^2 e^{\left[\frac{2}{3}-\frac{2}{3}\left(\frac{t}{t_{max}}\right)^3\right]}$$

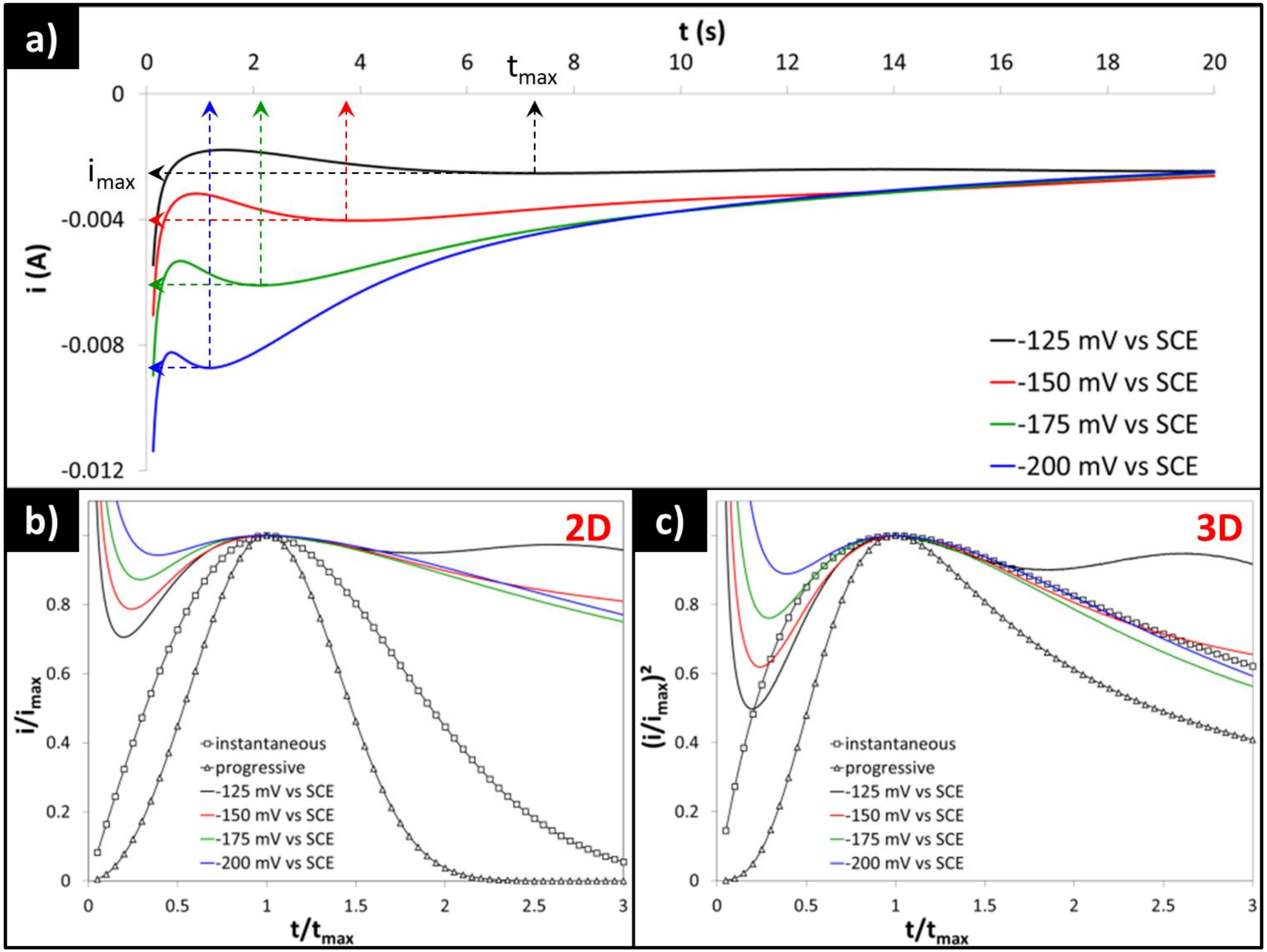
$$\left(\frac{i}{i_{max}}\right) = \left(\frac{t}{t_{max}}\right) e^{\left[\frac{1}{2}-\frac{1}{2}\left(\frac{t}{t_{max}}\right)^2\right]}$$

$$\left(\frac{i}{i_{max}}\right)^2 = 1.2254\left(\frac{t_{max}}{t}\right)\left[1 - exp^{-2.3367\left(\frac{t}{t_{max}}\right)^2}\right]^2$$

$$\left(\frac{i}{i_{max}}\right)^2 = 1.9542\left(\frac{t_{max}}{t}\right)\left[1 - exp^{-1.2564\left(\frac{t}{t_{max}}\right)}\right]^2$$

III) Nucleation and growth process

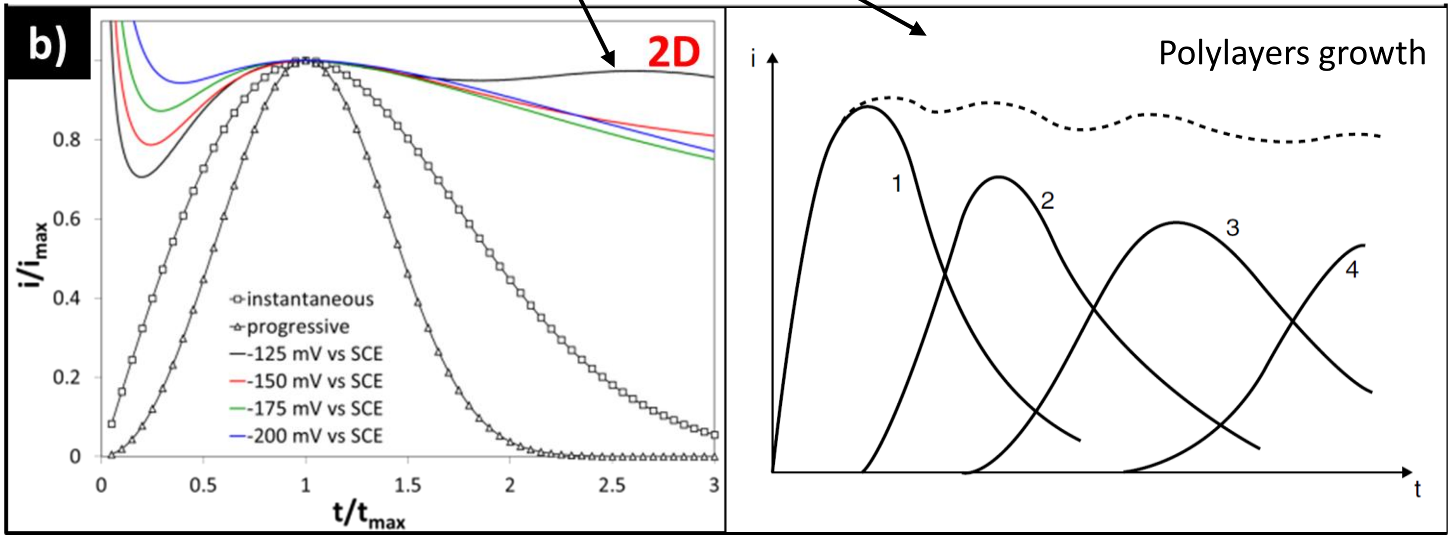
9) Nucleation and growth models



III) Nucleation and growth process

9) Nucleation and growth models

Successive nucleation and overlapping of 2D layers



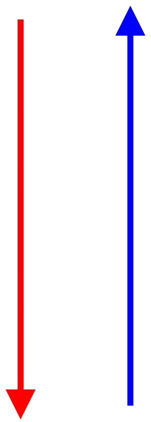
IV) Electrodeposit characteristics

Microstructure and morphology

Microstucture:

Atoms are arranged in 3 dimensions with a certain periodicity degree

- Monocrystalline: periodicity extends on the whole solid
- Polycrystalline: periodicity is interrupted at grain boundaries
- Nanocrystalline: periodicity extends over a few nanometers
- Amorphous: periodicity breaks at short distance (lattice parameter)



Ductility ↗

Hardness ↗
Brightness ↗
Brittleness ↗
Resistivity ↗

IV) Electrodeposit characteristics

Microstructure and morphology

Morphology: