# Crystal Growth: Physics, Technology and Modeling

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## Lecture 6. Kinetic processes at surfaces

**http://w3.unipress.waw.pl/~stach/cg-2022-23/**

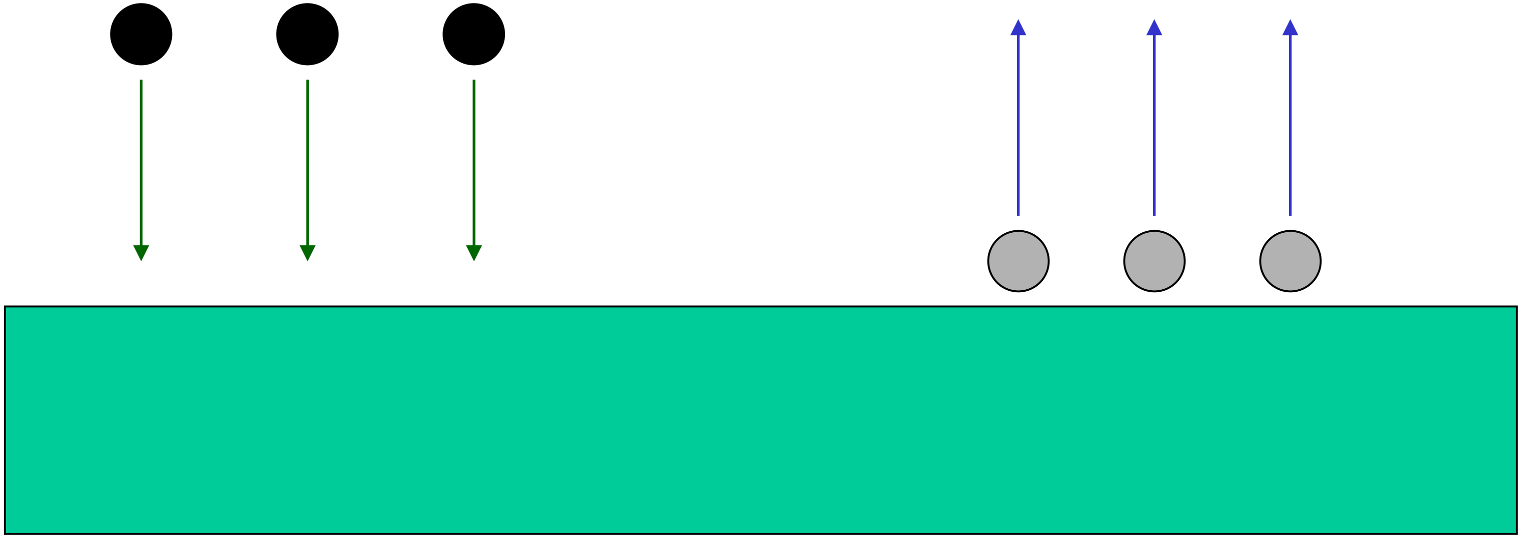
# Synopsis

- **Adsorption and desorption**
- **Surface diffusion**
- **Step Properties**
- **Motion of a system of parallel steps**
- **2-d nucleation**
- **Screw dislocations role in surface dynamics**

# Adsorption and desorption

- **Adsorption – attachment of species (molecules/atoms/radicals) at the solid/liquid surfaces**

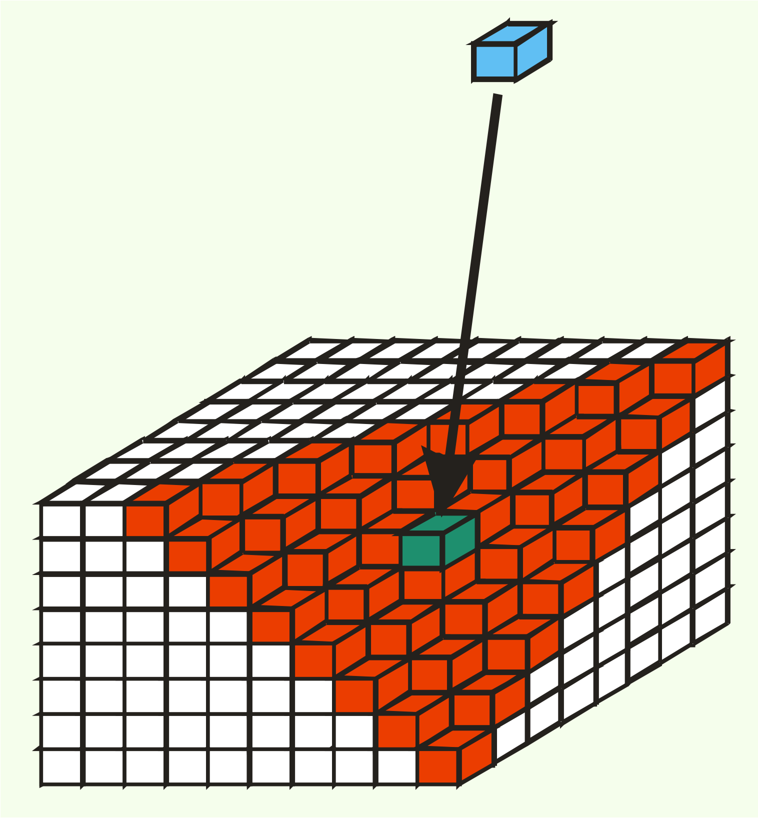
- **Desorption – detachment of the species from solid/liquid surfaces**

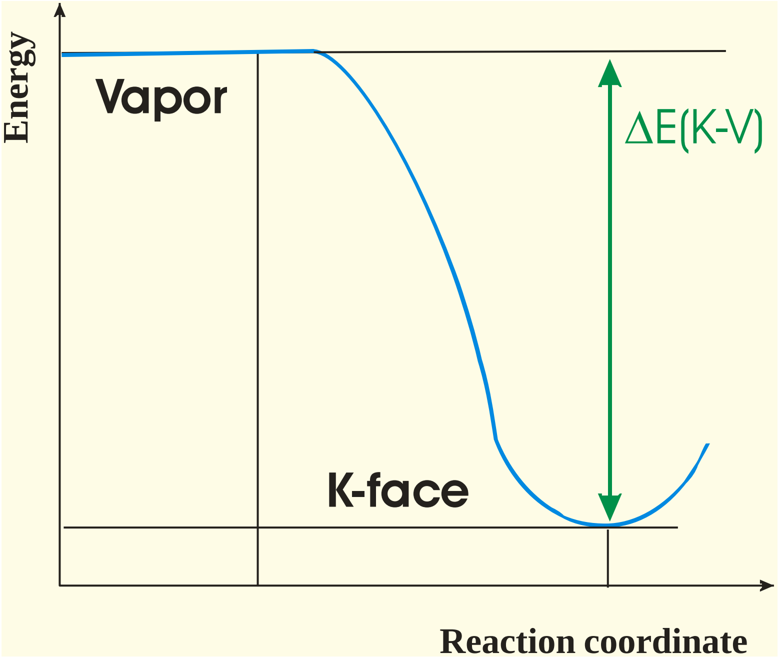


**Desorption does not depend on the pressure in the vapor**

# Adsorption –Kossel model – K surface

- **Atomic adsorption at K surface (atomically rough)**





$$E_K = -3\phi$$

$$E_V = 0$$

# K surfaces – fluxes and equilibrium

- **Adsorption – site attachment rate R$_{ads}$**

$$R_{ads} = \frac{p\varsigma}{\sqrt{2\pi mkT}} = n\varsigma\sqrt{\frac{kT}{2\pi m}}$$

- **Desorption – detachment rate R$_{des}$**

$$R_{des} = \nu\ exp\left[-\frac{3\phi}{kT}\right]$$

- **Equilibrium – fluxes are balanced R$_{tot}$**

$$R_{tot} = R_{ads} - R_{des} = \frac{p_{eq}\varsigma}{\sqrt{2\pi mkT}} - \nu\ exp\left[-\frac{3\phi}{kT}\right] = 0$$

- **Equilibrium – flux and pressure (will be used as reference value – i.e. zero supersaturation)**

$$R_{eq} = \nu\ exp\left[-\frac{3\phi}{kT}\right] \qquad p_{eq} = \frac{\nu\sqrt{2\pi mkT}}{\varsigma}\ exp\left[-\frac{3\phi}{kT}\right]$$

# K surface – growth rate

- **Growth rate - v**

$$v = I_{tot}d = [I_{ads}\varsigma - R_{des}]d = \frac{p\varsigma d}{\sqrt{2\pi mkT}} - \nu d\,exp\left[-\frac{3\phi}{kT}\right]$$

**d – atomic layer thickness (= a for Kossel crystal)**

- **Growth rate – in function of the pressure**

$$v = \frac{[p - p_{eq}]\varsigma d}{\sqrt{2\pi mkT}} = \frac{[p - p_{eq}]v_o}{\sqrt{2\pi mkT}}$$

$v_o = \varsigma d$ **(= a$^3$) – atomic volume**

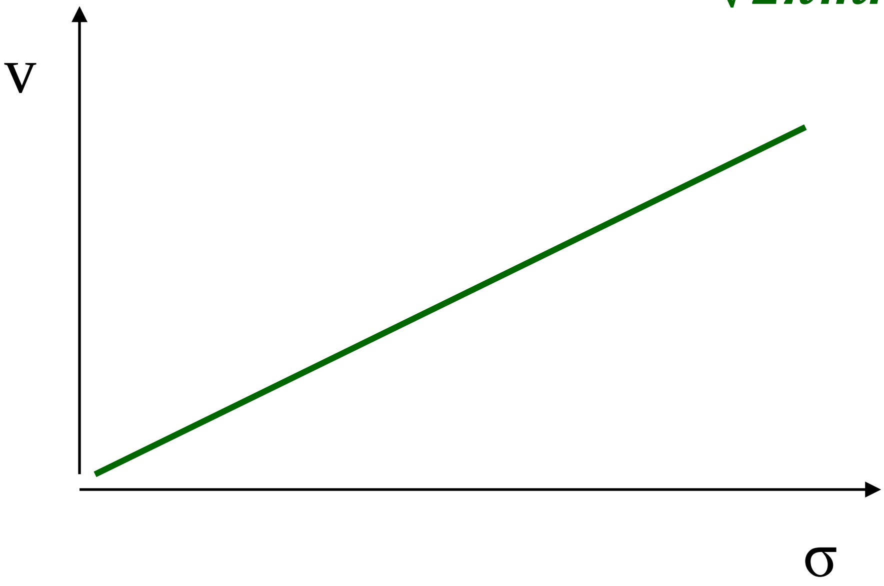
- **Growth rate – in function of the supersaturation - Wilson- Frenkel law**

$$v = \frac{p_{eq}v_o\sigma}{\sqrt{2\pi mkT}} = \sigma d\nu\,exp\left[-\frac{3\phi}{kT}\right]$$

# Wilson – Frenkel growth rate

- **Growth rate v**

$$v = \frac{p_{eq} v_o \sigma}{\sqrt{2\pi m k T}} = v d\sigma\, exp\left[-\frac{3\phi}{kT}\right]$$



$$v = 0.66\ cm/s$$

**This is the upper bound for crystal growth velocity at:**

**i/ $\sigma = 0.1$**

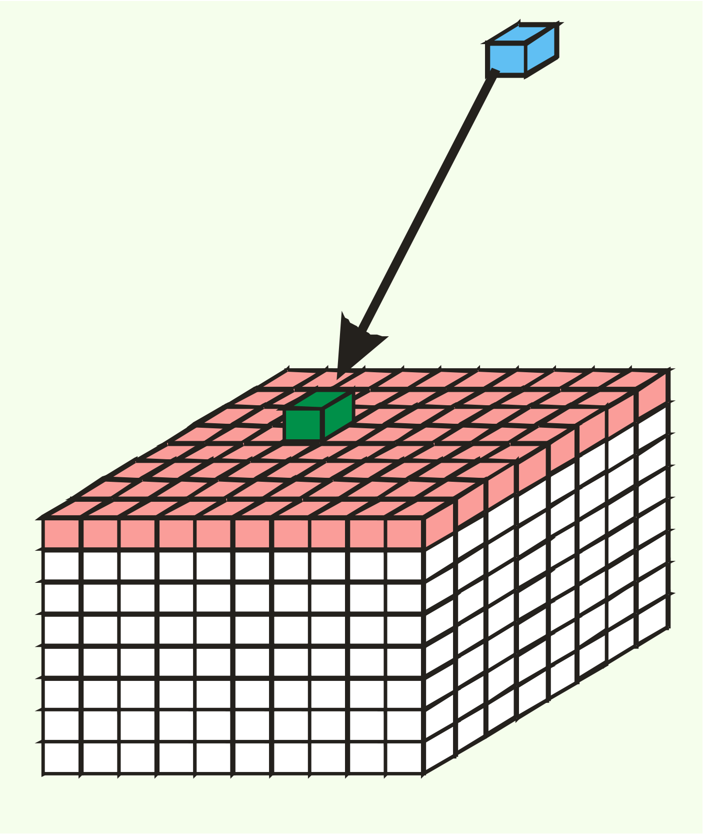
**ii/ $p = 1$ bar $= 10^5\ N/m^2$**

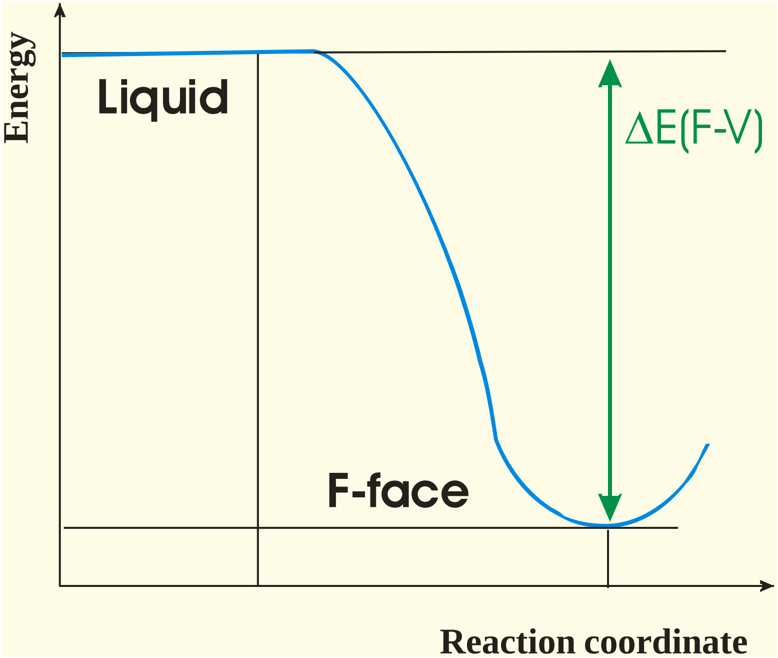
**iii/ $T = 298.15$ K**

**iv/ $m = m_{N2} = 28 * 1.66 * 10^{-27}$ kg**

# Adsorption – F surface (Kossel model)

- **Atomic adsorption at F surface (atomically flat)**





$E_F = -\phi$

$E_V = 0$

# Adsorption – at flat (F) surface

- **Adsorption – site attachment rate R$_{ads}$**

$$R_{ads} = I_{ads}\varsigma = \frac{p\varsigma}{\sqrt{2\pi mkT}} = n\varsigma\sqrt{\frac{kT}{2\pi m}}$$

- **Desorption – detachment rate R$_{des}$**

$$R_{des} = \nu c_{sur}(p)exp\left[-\frac{\phi}{kT}\right]$$

- **F surface – vapor – crystal equilibrium (zero supersaturation) – fluxes are balanced I$_{tot}$**

$$I_{tot} = \frac{p_{eq}}{\sqrt{2\pi mkT}} - \frac{\nu c_{sur-eq}}{\varsigma}\, exp\left[-\frac{\phi}{kT}\right] = 0$$

- **Site occupation (coverage) c$_{sur\text{-}eq}$**

$$c_{sur-eq} = exp\left[-\frac{2\phi}{kT}\right]$$

# Adsorption – at flat (F) surface- equilibrium with the crystal (K face)

- F surface – vapor in equilibrium with the crystal (K surface) – fluxes are balanced

$$I_{tot} = \frac{p_{eq}\varsigma}{\sqrt{2\pi mkT}} - \nu c_{sur-eq}\, exp\left[-\frac{\phi}{kT}\right] = 0$$

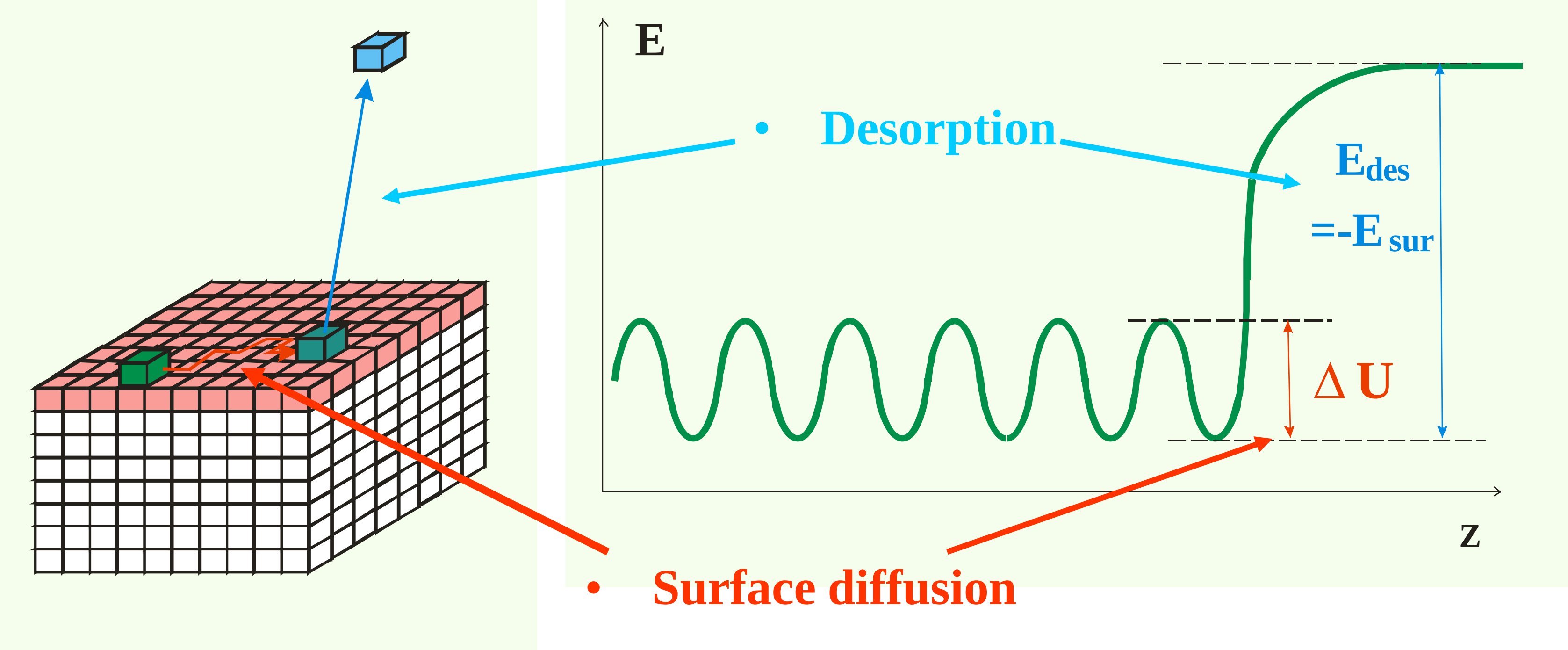
- Equilibrium with K face – flux and pressure

$$R_{eq} = \nu\, exp\left[-\frac{3\phi}{kT}\right]$$

- Site occupation in equilibrium (zero supersaturation) with the crystal and with vapor:

$$c_{sur-eq} = exp\left[-\frac{2\phi}{kT}\right]$$

# Flat surface – surface diffusion and desorption



- Desorption
- Surface diffusion

- **Surface diffusion coefficient depends on the jump barrier U:**

$$D = \frac{a^2\nu}{4} exp\left[-\frac{\Delta E_{diff}}{kT}\right] = \frac{a^2\nu}{4} exp\left[-\frac{U}{kT}\right]$$

# Flat (F) surface - desorption

- **Desorption – detachment rate $R_{des}$**

$$R_{des} = \nu\, exp\left[-\frac{E_{des}}{kT}\right] = \nu\, exp\left[-\frac{\phi}{kT}\right]$$

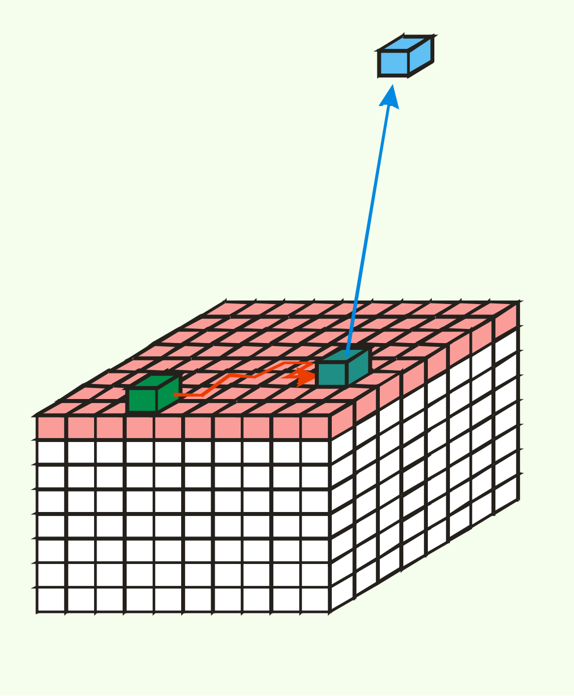
- **Surface residence time $\tau_{sur}$ – detachment rate**

$$\tau_{sur} = \frac{1}{\nu} exp\left[\frac{E_{des}}{kT}\right] = \tau_o exp\left(\frac{\phi}{kT}\right)$$

**The latter dependence is described for Kossel crystal F surface i.e. for $E_{des} = \phi$.**

# F surface – surface diffusion length

- **Surface diffusion lenght $x_{sur}$ is determined using surface residence time $\tau_{sur}$**



$$\langle(\Delta r)^2\rangle = 4D_{sur}t = 4D_{sur}\tau_{sur}$$

- **Surface diffusion coefficient**

$$D_{sur} = \frac{a^2\nu}{4} exp\left[-\frac{U}{kT}\right]$$

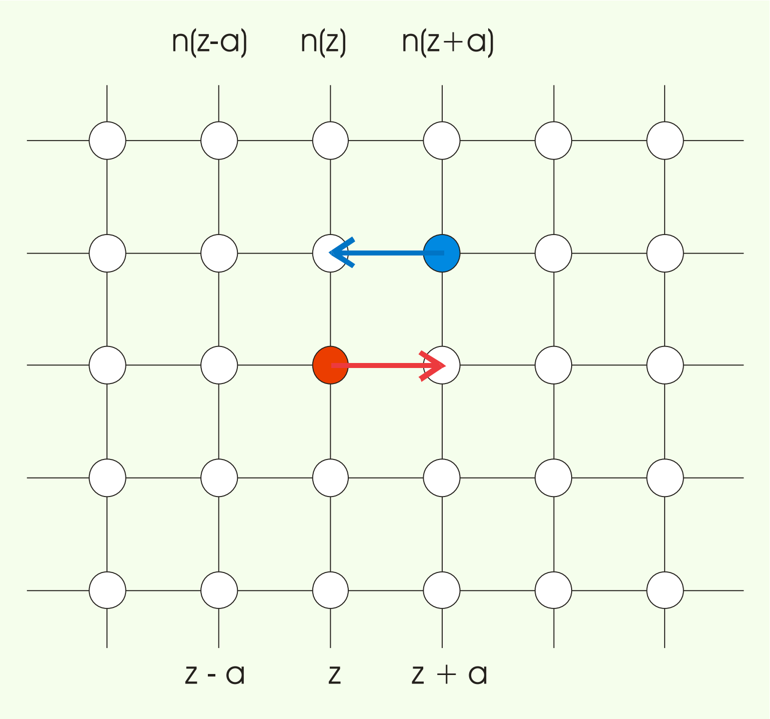
- **Surface diffusion length $x_{sur}$ is**

$$x_{sur} = \frac{a}{2}\, exp\left(-\frac{E_{des} - \Delta E_{diff}}{2kT}\right)$$

- **Kossel crystal**

$$x_{sur} = \frac{a}{2}\, exp\left(\frac{\phi - U}{2kT}\right)$$

# Surface diffusion – chemical diffusion



- **Average density of adsorbed species changes slowly in space:**

$$\boldsymbol{n_{sur}(z+a) = n_{sur} + \delta n_{sur}}$$

$$\boldsymbol{n_{sur}(z-a) = n_{sur} - \ \delta n_{sur}}$$

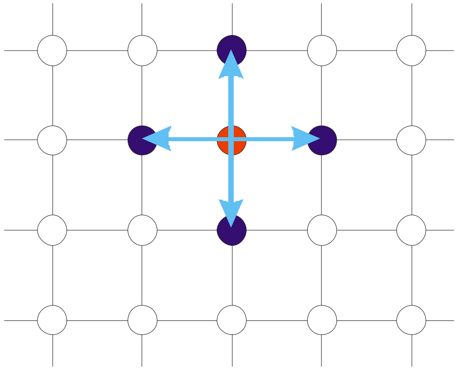
**i.e. over the distance a the change is small, and could be approximated by linear term.**

- **The velocity of the jump of the species to the right and left is**

$$\boldsymbol{R(z \to z+a) = n_{sur}(z)\nu P(z \to z+a)}$$

$$\boldsymbol{R(z+a \to z) = n_{sur}(z+a)\nu P(z+a \to z)}$$

# Surface diffusion (chemical) - Fick law



- **Effective flux is the difference of these jumps**

$$j_{sur} = R(z \to z + a) - R(z + a \to z)$$

- **Linear expansion gives**

$$j_{sur} = -\left(\frac{dn_{sur}}{dz}\right) a\, \nu P(z \to z + a)$$

$$P(z \to z + a) = \frac{1}{4}$$

$$j_{sur} = -\frac{a^2\nu}{4}\left(\frac{dn_{sur}}{dz}\right) = -D_{sur}\left(\frac{dn_{sur}}{dz}\right)$$

- **General case – Fick law**

$$\vec{j}_{sur} = -D_{sur}\nabla n_{sur} = -D_{sur}\eta\nabla c_{sur}$$

**$c_{sur}$ – coverage, i.e. fraction of sites that are occupied**

# Adsorbate dynamics

- **Mass conservation law (next lecture – derivation)**

$$\nabla \cdot \vec{j}_{sur} + I = 0$$

- **Mass source for unit of surface area *I* – adsorption and desorption balance**

$$I = I_{ads} - I_{des}$$

- **Adsorbate dynamics equation**

$$D_{sur} \Delta n_{sur} = I_{ads} - I_{des}$$

# Sources – adsorption and desorption

- **Vapor mass sources are calculated using vapor supersaturation $\sigma_V$:**

$$\sigma_V = \frac{p - p_{eq}}{p_{eq}}$$

- **Surface supersaturation, different from vapor supersaturation is;**

$$\sigma = \frac{n_{sur} - n_{sur-eq}}{n_{sur-eq}} = \frac{c_{sur} - c_{sur-eq}}{c_{sur-eq}}$$

- **Adsorbate density:**

$$n_{sur} = \eta c_{sur} = \frac{c_{sur}}{\varsigma}$$

- **The effective source (i.e. from the vapor) is:**

$$I = I_{ads} - I_{des} = \frac{p}{\sqrt{2\pi mkT}} - \frac{\nu c_{sur}}{\varsigma} \, exp\left[-\frac{\phi}{kT}\right]$$

# Adsorbate dynamics - sources

- **Laplace term is:**

$$D_{sur}\Delta n_{sur} = D_{sur}\eta\Delta c_{sur} = \frac{D_{sur}\Delta\left(c_{sur} - c_{sur-eq}\right)}{\varsigma} = \frac{D_{sur}c_{sur-eq}\Delta\sigma}{\varsigma}$$

- **Vapor mass source is:**

$$I_{ads} = \frac{p}{\sqrt{2\pi mkT}} = \frac{\nu\sigma_V c_{sur-eq}}{\varsigma}\ exp\left[-\frac{\phi}{kT}\right] = \frac{\sigma_V c_{sur-eq}}{\varsigma\tau_{sur}}$$

- **Desorption escape is:**

$$I_{des} = \frac{\nu c_{sur}}{\varsigma}\ exp\left[-\frac{\phi}{kT}\right] = \frac{\nu\sigma c_{sur-eq}}{\varsigma}\ exp\left[-\frac{\phi}{kT}\right] = \frac{\sigma c_{sur-eq}}{\varsigma\tau_{sur}}$$

# Adsorbate dynamics - sources

- **The basic equation is:**

$$\frac{D_{sur}c_{sur-eq}\Delta\sigma}{\varsigma} = \frac{\sigma c_{sur-eq}\tau_{sur}}{\varsigma} - \frac{\sigma_V c_{sur-eq}\tau_{sur}}{\varsigma}$$

- **Transferred to:**

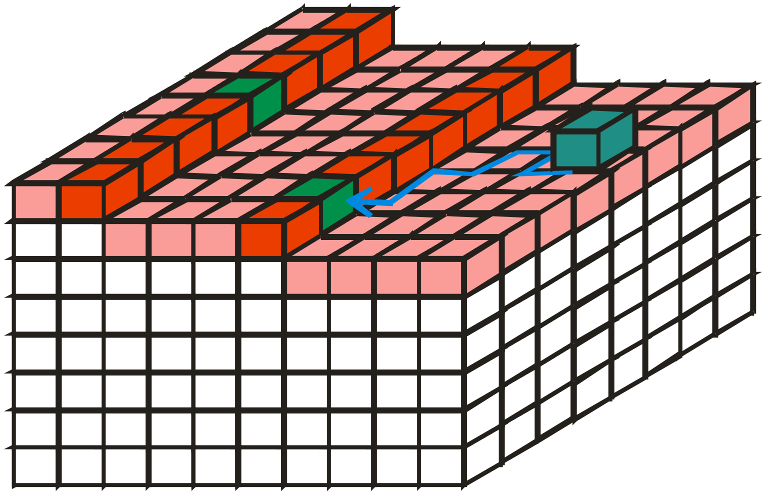
$$\frac{D_{sur}\Delta\sigma}{\tau_{sur}} = \sigma - \sigma_V$$

- **The fundamental equation is:**

$$x_{sur}^2\Delta\sigma = \sigma - \sigma_V$$

# Vicinal (V) surfaces – steps and terraces

**Surfaces consisting of steps and flat areas between (terraces) we call vicinal surfaces.**

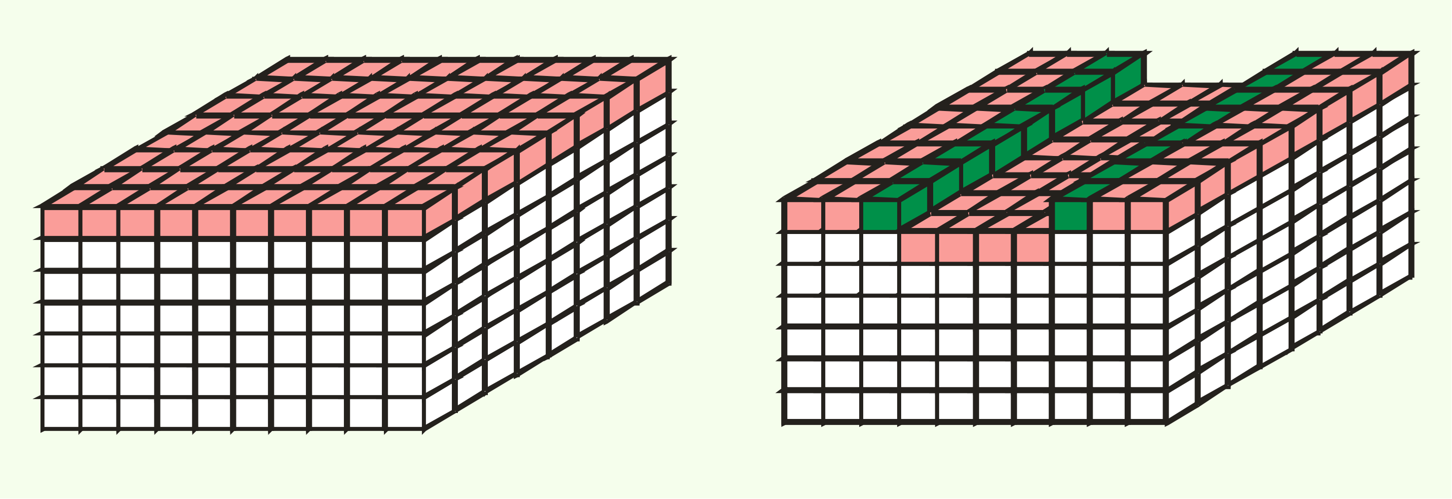


- **The fundamental equation is governing adsorbate dynamics at terraces:**

$$x_{sur}^{2}\Delta\sigma = \sigma - \sigma_{V}$$

- **Steps – boundary conditions?**

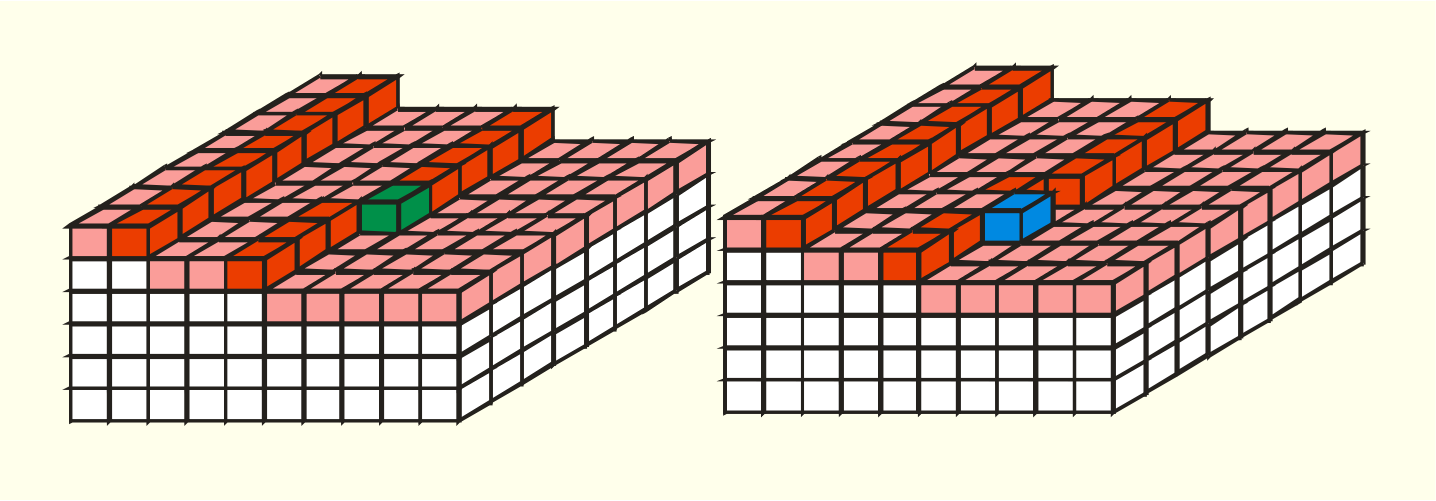
# Energy of the steps



- **Atom row escape - creation of two steps**
- **Atom escape  - two bonds are broken**
- **Step energy in a distance – half of the bond energy**

$$\gamma = \frac{\phi}{2}$$

# Step- kink creation



- **Atom escape - creation of two kinks**
- **Atom escape  - two bonds are broken**
- **Kink energy – half of the bond energy**

# Microscopic structure of the steps

- **Atom escape - creation of two kinks**
- **Atom escape - two bonds are broken**
- **Kink concentration at the step:**

$$c_{kink} = P\left(\frac{E_{kink}}{2}\right) = exp\left(-\frac{\phi}{2kT}\right)$$

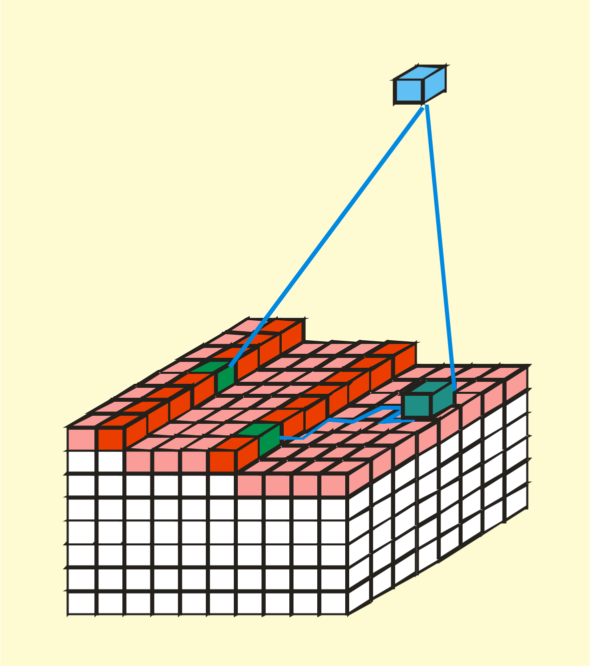
- **Kink concentration at the step is strongly temperature dependent. Nevertheless in typical growth experiment it is high. The distance between two kinks is**

$$l_{kink} = \frac{a}{2c_{kink}} = \frac{a}{2} exp\left(\frac{\phi}{2kT}\right)$$

# Steps – linear growth sources Burton, Cabrera Frank (BCF) model

**Atoms/molecules are incorporated at the steps from:**

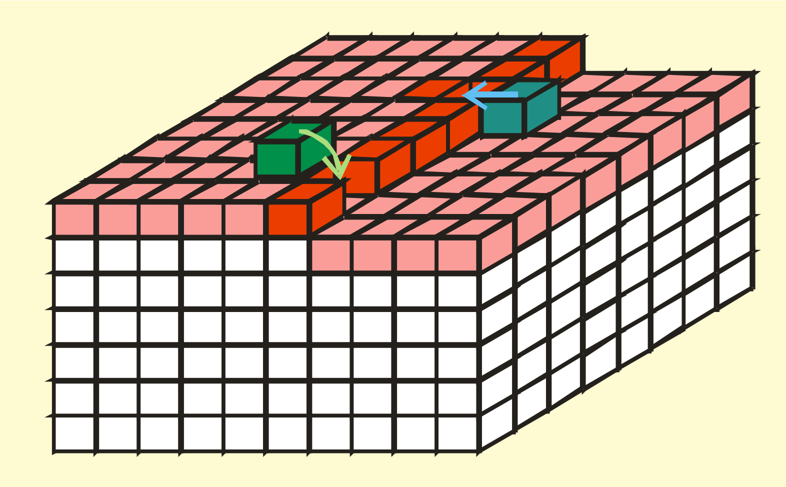
- **Diffusion at terraces**
- **From the vapor directly**



***W.K. Burton, N. Cabrera & F.C. Frank, Philosph. Trans. Roy. Soc. (London) A243 (1951) 299***

# Symmetry of the steps

- **Symmetric steps - jump barrier from upper and lower are identical**
- **Asymmetric steps - jump barrier from upper and lower are different**



- **Step asymmetry – Schwoebel barrier**

***R.L. Schwoebel & E.J. Shipsey, J. Appl. Phys. 37 (1966) 3682***

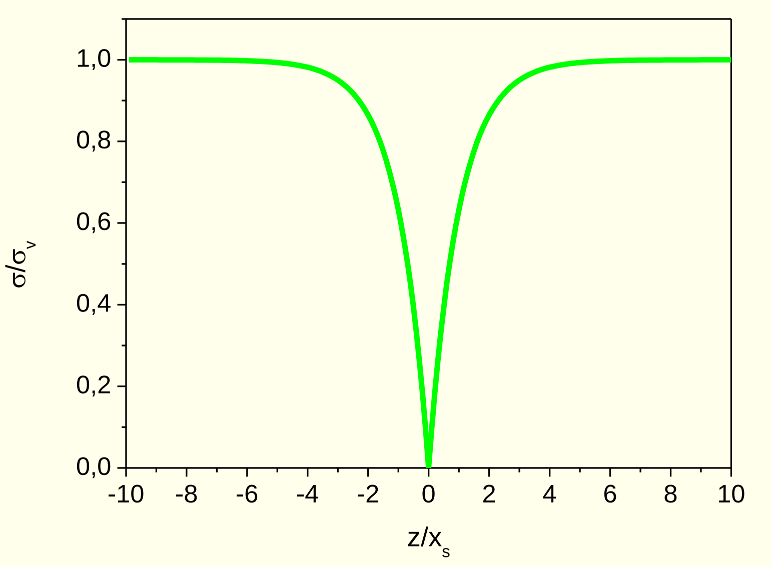
***R.L. Schwoebel, J. Appl. Phys. 40 (1969) 614***

# Symmetric steps – simple model dynamics

- **Jumps are equally probable from upper and lower terrace**
- **No additional energy barrier for terrace-step jump**
- **Simple model – supersaturation at the step vanishes**

- **Terrace dynamics**

$$x_{sur}^2 \Delta\sigma = \sigma - \sigma_V \qquad x_{sur}^2 \frac{d^2\sigma}{dz^2} = \sigma - \sigma_V$$



- **Boundary condition at the step**

$$\sigma = 0 \qquad z = 0$$

- **Solution**

$$\sigma = \sigma_V[1 - exp(-z/x_{sur})] \qquad z > 0$$

$$\sigma = \sigma_V[1 - exp(z/x_{sur})] \qquad z < 0$$

# Motion of single, symmetric step

- Adatom flux to the step $I_{step}$

$$I_{step} = 2j_{sur}(z = 0) = 2D_{sur}\eta c_{sur-eq}\nabla\sigma = \frac{2D_{sur}\eta c_{sur-eq}\sigma_V}{x_{sur}}$$

- Step site atom attachment frequency $R_{step}$

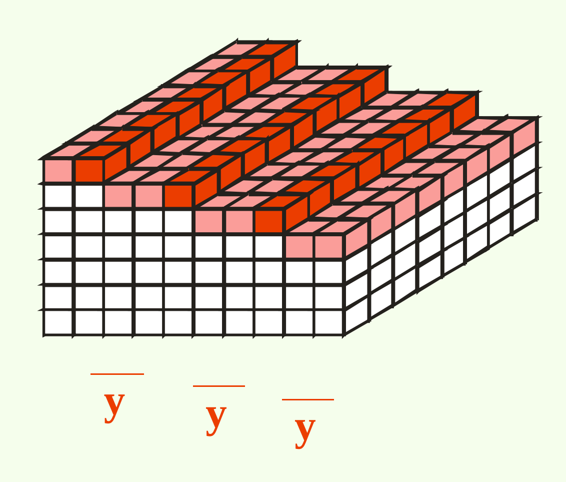
$$R_{step} = I_{step}a = \frac{2D_{sur}\eta c_{sur-eq}\sigma_V a}{x_{sur}}$$

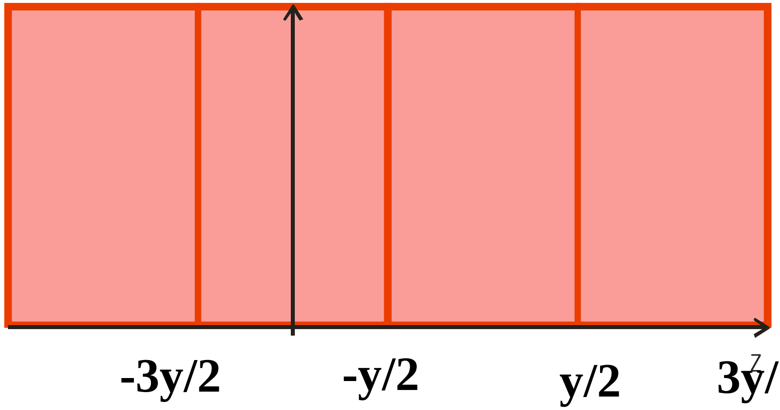
- Step velocity $v_{step}$

$$v_{step} = R_{step}a = \frac{2D_{sur}\eta c_{sur-eq}\sigma_V a^2}{x_{sur}} = \frac{2x_{sur}c_{sur-eq}\sigma_V}{\tau_{sur}}$$

# Parallel equidistant symmetric steps - dynamics

- **Step distance y:**





- **Solution (single terrace)**

$$\sigma = \sigma_V \left[ 1 - \frac{csh(z/x_{sur})}{csh(y/2x_{sur})} \right]$$

- **Terrace dynamics**

$$x_{sur}^2 \frac{d^2\sigma}{dz^2} = \sigma - \sigma_V$$

- **Periodicity (multiple terraces)**

$$\sigma = \sigma_V \left[ 1 - \frac{csh[(z-2ny)/x_{sur}]}{csh(y/2x_{sur})} \right]$$

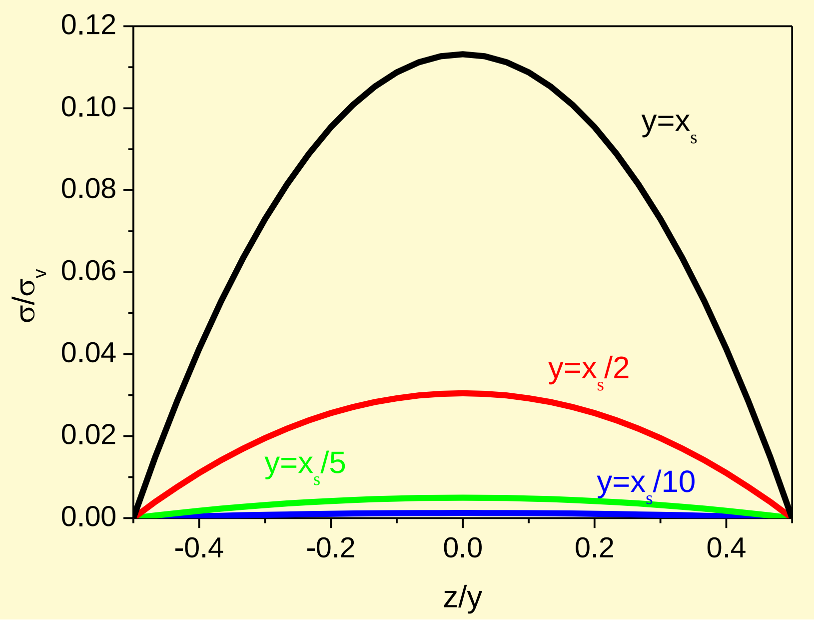
- **Boundary condition at the step**

$$\sigma = 0 \qquad z = \pm\frac{y}{2}, \pm\frac{3y}{2}, \frac{5y}{2}, \dots,$$

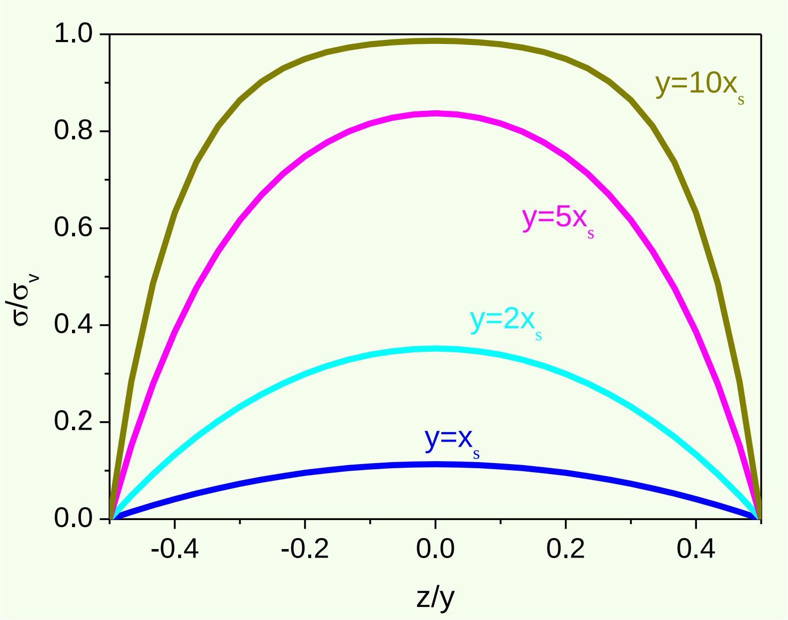
$$n = 0, \pm 1, \pm 2, \pm 3, \dots$$

# Parallel equidistant symmetric steps - supersaturation

$$\sigma = \sigma_V \left[ 1 - \frac{csh(z/x_{sur})}{csh(y/2x_{sur})} \right] \qquad -\frac{y}{2} \leq z \leq \frac{y}{2}$$



$y \leq x_{sur}$



$y \geq x_{sur}$

# Parallel equidistant symmetric steps – step motion

- **Adatom flux to the step $I_{step}$**

$$I_{step} = 2D_{sur}\eta c_{sur-eq}\nabla\sigma = \frac{2D_{sur}\eta c_{sur-eq}\sigma_V}{x_{sur}}\tanh\left(\frac{y}{2x_{sur}}\right)$$

- **Step site atom attachment frequency $R_{step}$**

$$R_{step} = I_{step}a = \frac{2D_{sur}\eta c_{sur-eq}\sigma_V a}{x_{sur}}\tanh\left(\frac{y}{2x_{sur}}\right)$$

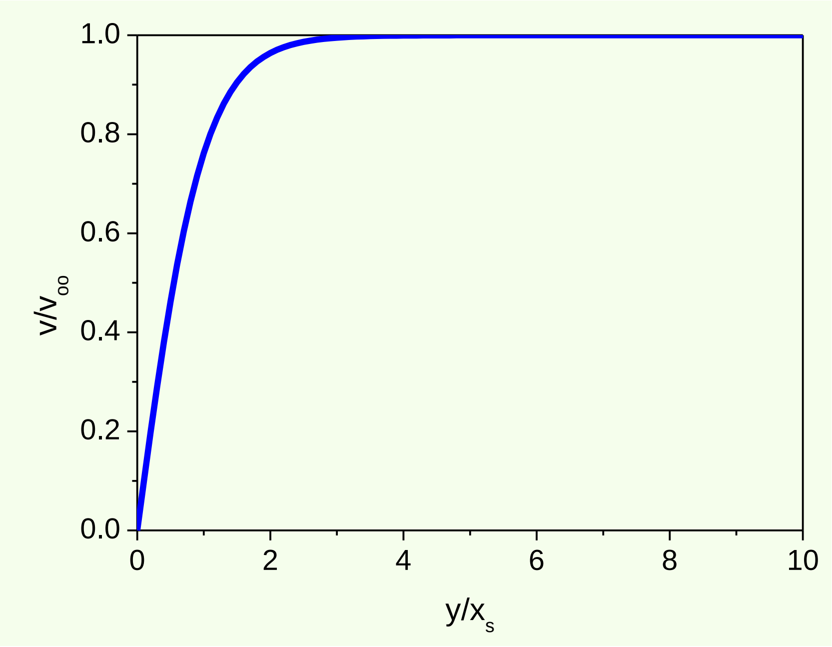
- **Steps velocity $v_{step}$(y)**

$$v_{step}(y) = R_{step}a = \frac{2x_{sur}c_{sur-eq}\sigma_V}{\tau_{sur}}\tanh\left(\frac{y}{2x_{sur}}\right)$$

# Parallel symmetric steps – step motion – distance dependence

- **Parallel steps velocity $v_{step}$(y)**

$$v_{step}(y) = \frac{2x_{sur}c_{sur-eq}\sigma_V}{\tau_{sur}}\tanh\left(\frac{y}{2x_{sur}}\right)$$



- **Single step velocity $v_\infty = v_{step}(\infty)$**

$$v_{step}(\infty) = \frac{2x_{sur}c_{sur-eq}\sigma_V}{\tau_{sur}}$$

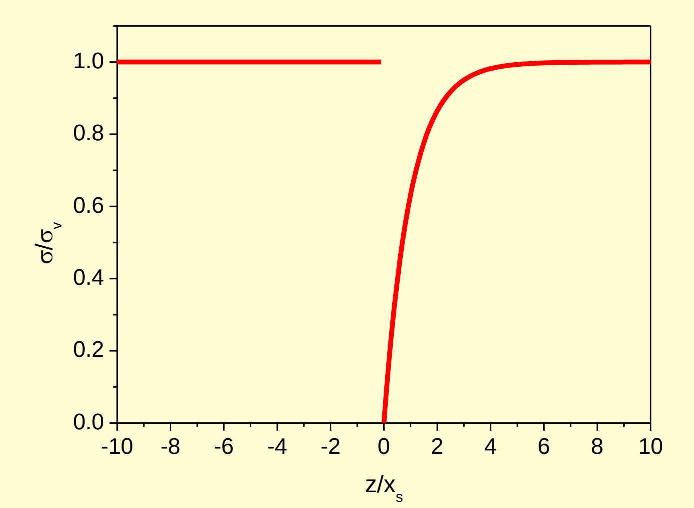
***Small interstep distance – low velocity – diffusional repulsion of the steps***

# Asymmetric steps – simple model dynamics

- **Jumps from upper and lower terrace have different barriers**
- **Simple model – supersaturation at the step vanishes**

- **Terrace dynamics**

$$x_{sur}^2 \Delta\sigma = \sigma - \sigma_V \qquad x_{sur}^2 \frac{d^2\sigma}{dz^2} = \sigma - \sigma_V$$



- **Boundary condition at the step – lower terrace**

$$\sigma = 0 \qquad z = 0_+$$

- **Boundary condition at the step – upper terrace**

$$j = 0 \qquad z = 0_-$$

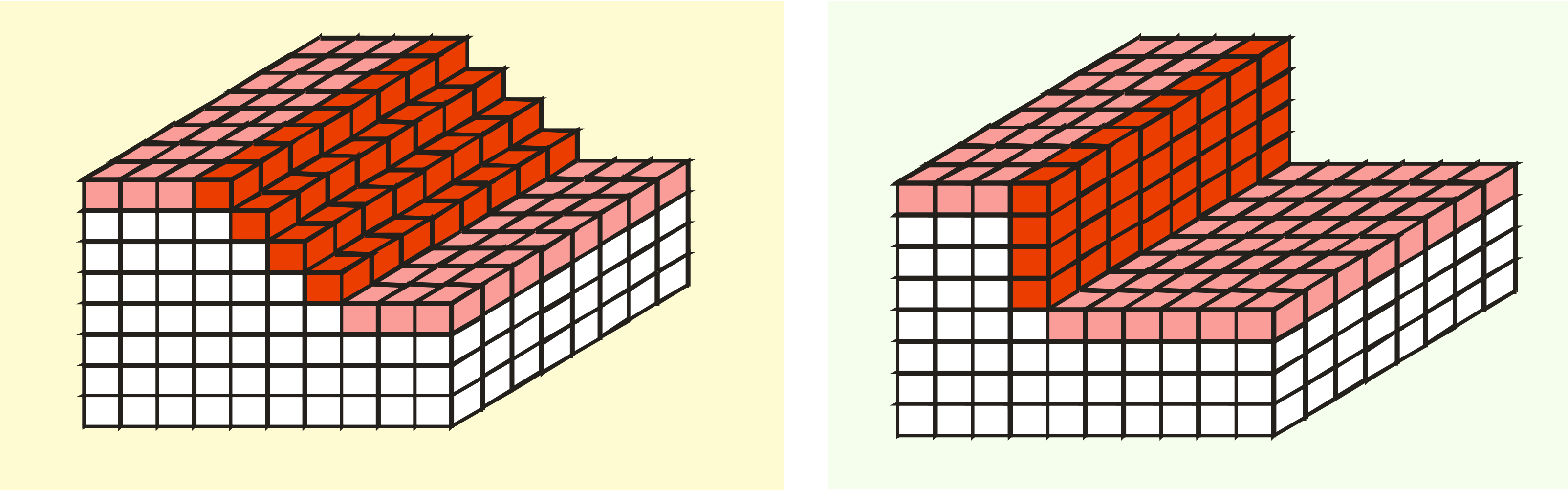
- **Solution**

$$\sigma = \sigma_V[1 - exp(-z/x_{sur})] \qquad z > 0$$

$$\sigma = \sigma_V \qquad z < 0$$

# Parallel asymmetric steps - macrosteps

- **Macrostep – stack of many atomic steps, at the same position**



- **Macrosteps – coalescence of a number of atomic steps**
- **Symmetric steps repel each other – no macrosteps creation tendency**
- **This conclusion is independent of the step orientation**
- **Additional factor can contribute to macrostep formation – impurities, kink poisoning, etc.**

# Steps – sources and geometry

## Sources

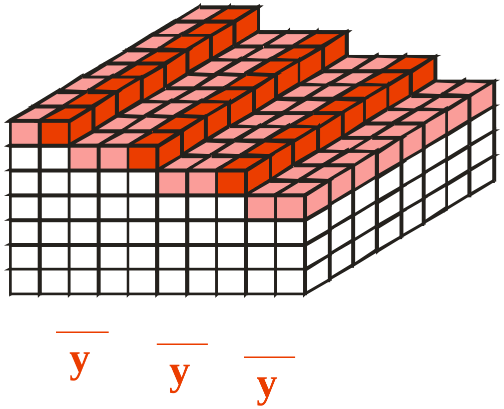
- Surface preparation for epitaxy
- Two-dimensional nucleation
- Screw dislocation – continuous step source
- Other extended defects, such as stacking faults

## Geometry

- Microstructure – equilibrium
- Macrostructure – step shape – purely nonequilibrium, history dependent
- Step height - purely nonequilibrium, history dependent

# Steps created by surface preparation

- **Surface misorientation – small angle to low Miller indices surface e.g. $2^{o}$ on GaN surface**



**Sample size l = 5 mm**

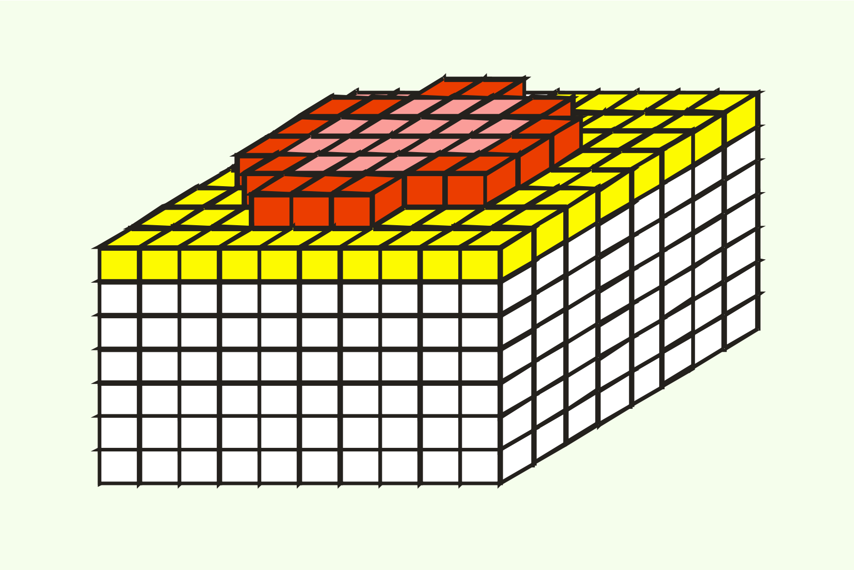
**Layer thickness – d**

$$d = l\,tg(\alpha) = 172\ \mu m$$

**This is more than sufficient for typical optoelectronic device where the structure is 1 micron thick**

# Step source – 2-d nucleation

- **Fluctuation – emergence of finite island of a new atomic layer:**



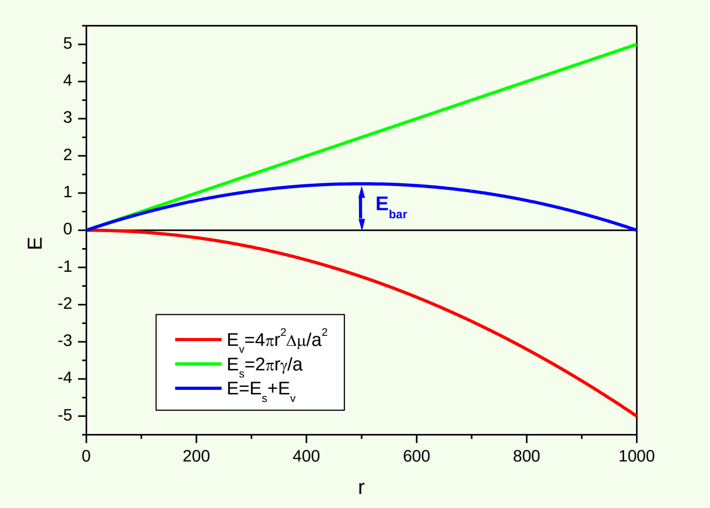
- **Edge energy of the length a - γ**

- **Single site area $s_o = a^2$**

- **Supersaturation**

$$\sigma = \frac{\Delta\mu}{kT}$$

# Nucleation energy barrier



- **Total energy change in island creation:**

$$\Delta E = \frac{\pi r^2 \Delta\mu}{a^2} + \frac{2\pi r\gamma}{a}$$

- **Positive term is due to edge energy, $\gamma > 0$**

- **Negative term is due to bulk energy, $\Delta\mu < 0$**

- **Positive term dominates at small r, negative for large r, the maximum energy, at critical radius is called nucleation barrier**

$$r_{crit} = -\frac{\gamma a}{\Delta\mu} = \frac{\gamma a}{|\Delta\mu|} = \frac{\gamma a}{kT\sigma} = \frac{\phi a}{2|\Delta\mu|} \qquad \gamma = \frac{\phi}{2}$$

- **Nucleation barrier**

$$\Delta E_{bar} = \frac{\pi\gamma^2}{|\Delta\mu|} = \frac{\pi\phi^2}{4|\Delta\mu|}$$

# 2-d nucleation rate (Zeldowich)

- **Nucleation rate – attempt frequency ν, number of sites at circumference $N_s$, and transition probability**

$$R_{2d-nucl} = \nu\, n_c\, P = \nu \frac{2\pi r_{crit}}{a}\, exp\left(-\frac{\Delta E_{bar}}{kT}\right)$$

- **Nucleation rate – for single nucleus**

$$R_{2d-nucl} = \frac{2\pi\nu\gamma}{|\Delta\mu|}\, exp\left(-\frac{\pi\gamma^2}{kT|\Delta\mu|}\right) = \frac{\pi\nu\phi}{|\Delta\mu|}\, exp\left(-\frac{\pi\phi^2}{4kT|\Delta\mu|}\right)$$

- **Nucleation rate – for crystal surface A**

$$\gamma = \frac{\phi}{2}$$

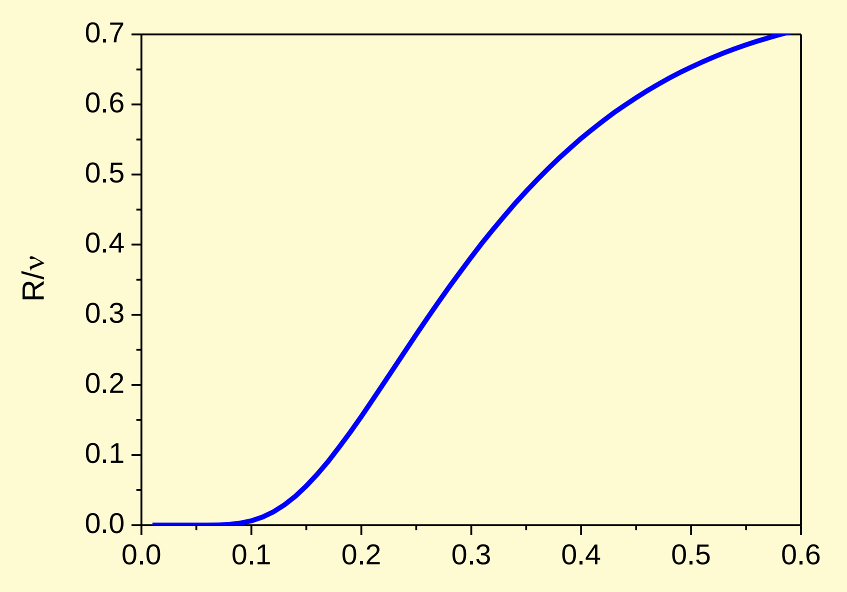
$$R_{2d-nucl}(A) = R_{2d-nucl} \frac{A}{\pi r_{crit}^2} = \frac{2\nu A|\Delta\mu|}{\gamma a^2}\, exp\left(-\frac{\pi\gamma^2}{kT|\Delta\mu|}\right)$$

$$R_{2d-nucl}(A) = \frac{\nu A|\Delta\mu|}{\phi a^2}\, exp\left(-\frac{\pi\phi^2}{4kT|\Delta\mu|}\right)$$

# 2-d nucleation rate – supersaturation dependence

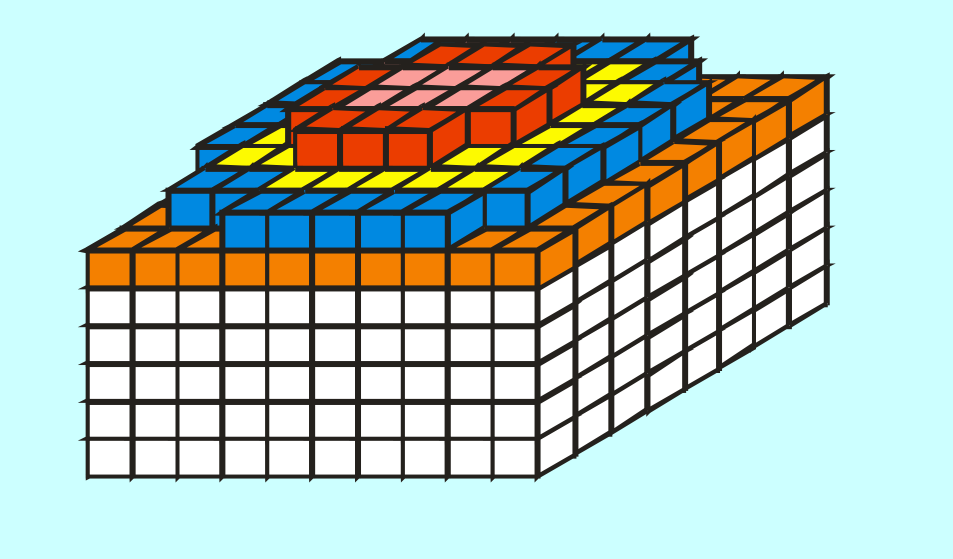
- **Nucleation rate at the surface area A:**

$$R_{2d-nucl}(A) = \frac{\nu A|\Delta\mu|}{\phi a^2}\, exp\left(-\frac{\pi\phi^2}{4kT|\Delta\mu|}\right)$$



# 2-d nucelation – macrostep generation

- **2-d nucleation could be fast as compared to layer completion, - creation of macrosteps is possible**



**Growth – size increase of concentric circles**

# Growth of concentric circles

- **Supersaturation at curved step is reduced by Gibbs-Thomson effect:**

$$\boldsymbol{\sigma(r) = \sigma\left(1 - \frac{r_{crit}}{r}\right)}$$

**$r_{crit}$ – critical nucleation radius (2d)**

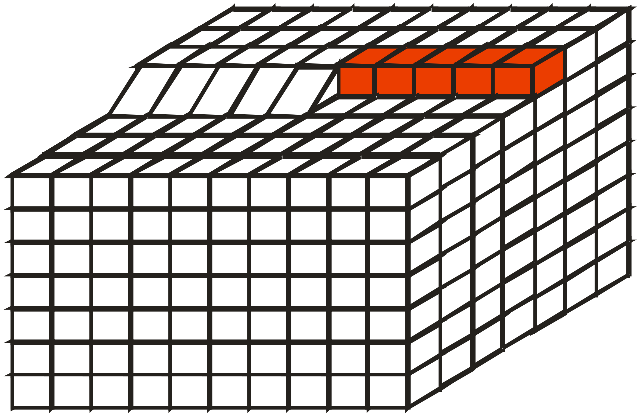
$$\boldsymbol{r_{crit} = -\frac{\gamma a}{\Delta\mu} = \frac{\gamma a}{|\Delta\mu|} = \frac{\gamma a}{kT\sigma} = \frac{\phi a}{2|\Delta\mu|}}$$

- **Velocity $v_{step}$(y) of the curved steps, separated by the distance y:**

$$\boldsymbol{v_{step}(y) = \frac{2D_{sur}\eta c_{sur-eq}\sigma_V a^2}{x_{sur}}\tanh\left(\frac{y}{2x_{sur}}\right)\left(1 - \frac{r_{crit}}{r}\right)}$$

# Step sources – screw dislocations

- **Dislocation atomic structure**



- **In equilibrium step is straight line.**

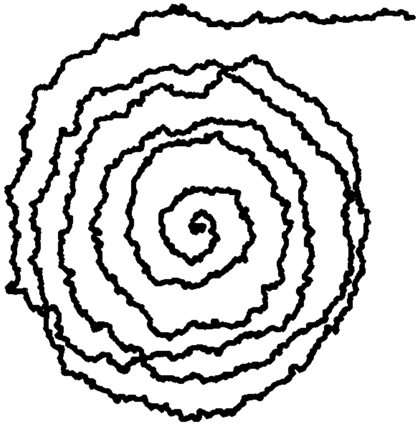
# Supercooling – step is curved

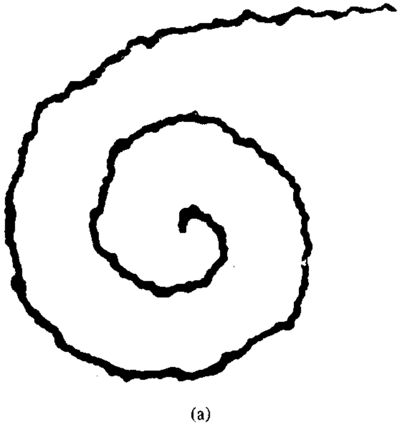
- **High temperature – Archimedean spiral**

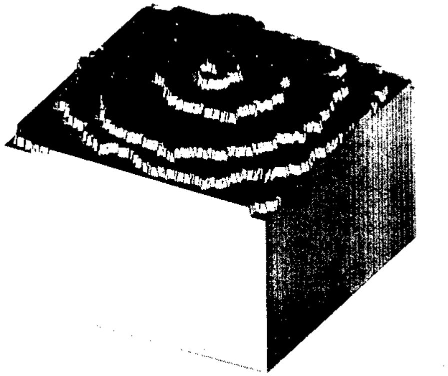
**High supersaturation**

$$\sigma = \frac{\Delta\mu}{kT} = 0.4$$

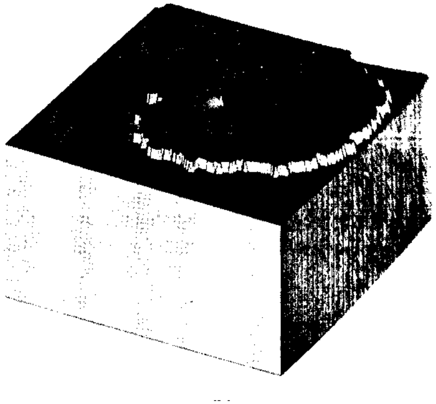
**Low supersaturation**







$$\sigma = \frac{\Delta\mu}{kT} = 0.1$$



*R. H. Swendsen et al. J. Cryst. Growth 35 (1976) 73*

# Step motion – spiral rotation – Archimedean spiral

- **Step velocity depends on the curvature:**

$$v_{step}(r) = v_{step}\left(1 - \frac{r_{crit}}{r}\right)$$

- **Approximate solution- Archimedean spiral:**

$$r(\theta) = 2r_{crit}\theta$$

- **Angular velocity is:**

$$\omega = \frac{v_{step}}{2r_{crit}}$$

- **Distance between spiral arms is:**

$$y_o = 2\pi r_{crit}$$

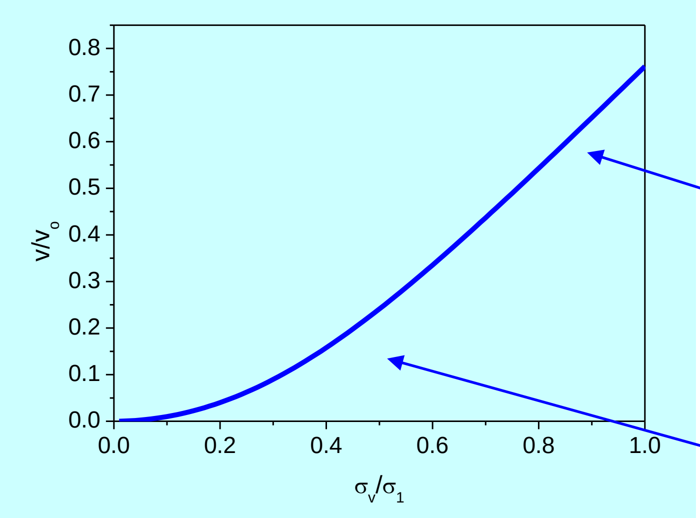
- **Spiral shape is function of the supersaturation**

- **Spiral velocity depends on the surface diffusion rate**

# Spiral dislocation controlleed growth rate

- **Growth rate is equal to the angular velocity ω multiplied by layer thickness a:**

$$v=\frac{\omega a}{2\pi}=\frac{v_{step}a}{2r_{crit}}=\frac{a\sigma_V^2}{\sigma_1\tau_{sur}}\tanh\left(\frac{\sigma_1}{\sigma_V}\right)\cong\begin{cases}\dfrac{a\sigma_V^2}{\sigma_1\tau_{sur}} & \sigma_V\ll\sigma_1\\[2ex] \dfrac{a\sigma_V}{\tau_{sur}} & \sigma_V\gg\sigma_1\end{cases}$$



$$\sigma_1=\frac{\pi\gamma a}{2kTx_{sur}}=\left(\frac{a}{x_{sur}}\right)\left(\frac{\pi\phi}{4kT}\right)$$

**linear**

**parabolic**

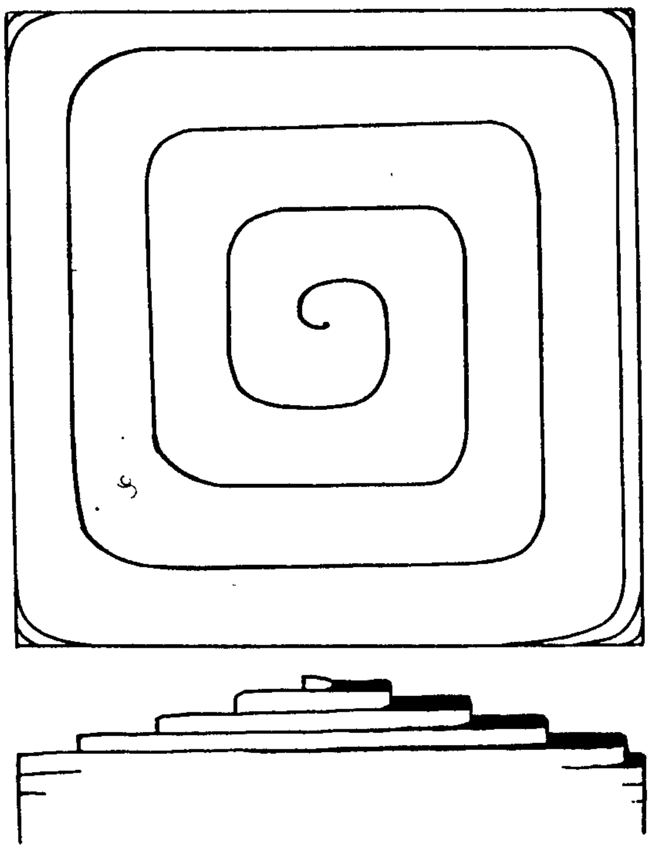
# Screw dislocation – growth pyramid.

- **Distance between spiral line is:**

$$y_o = 4\pi r_{crit} =$$

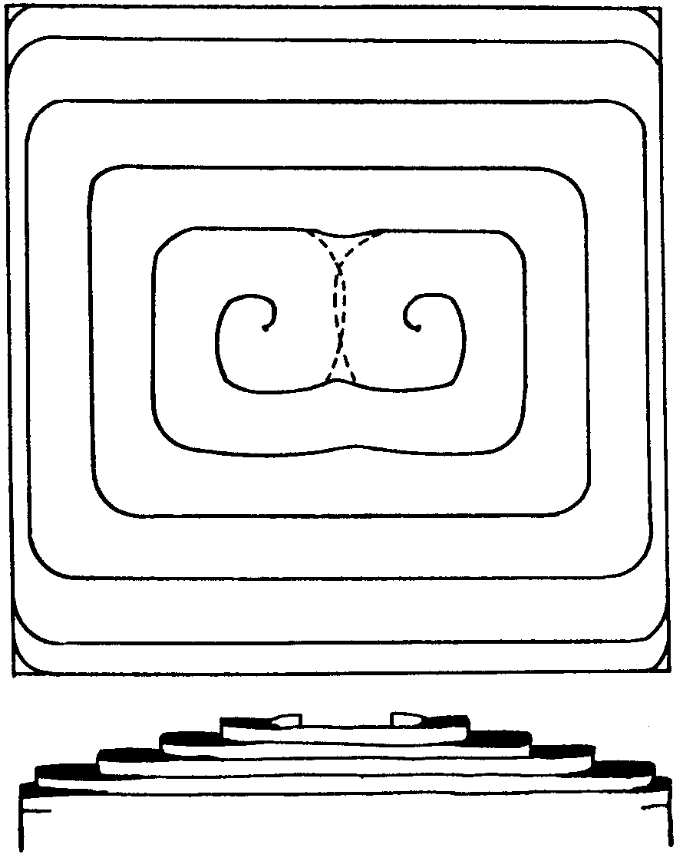
$$\frac{\pi\gamma a}{k_B T\sigma_v} = \frac{\pi\varphi a}{k_B T\sigma_v}$$

$$\mathrm{tg}\alpha = \frac{a}{y_o} = \frac{4k_B T\sigma_v}{\varphi}$$

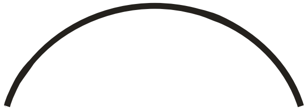


# Two dislocations of the opposite sign

**L – distance between dislocations**

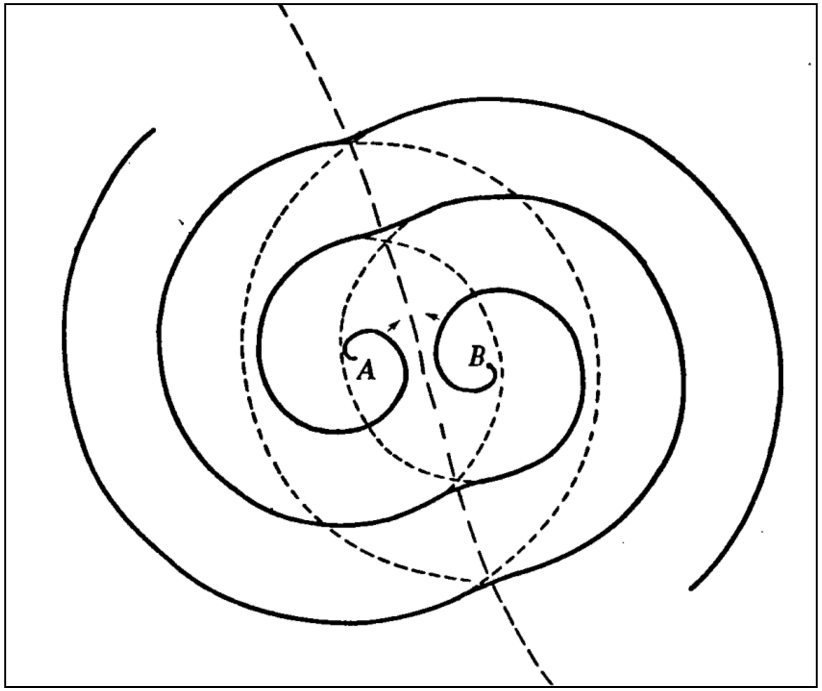


**$L > r_{crit}$**

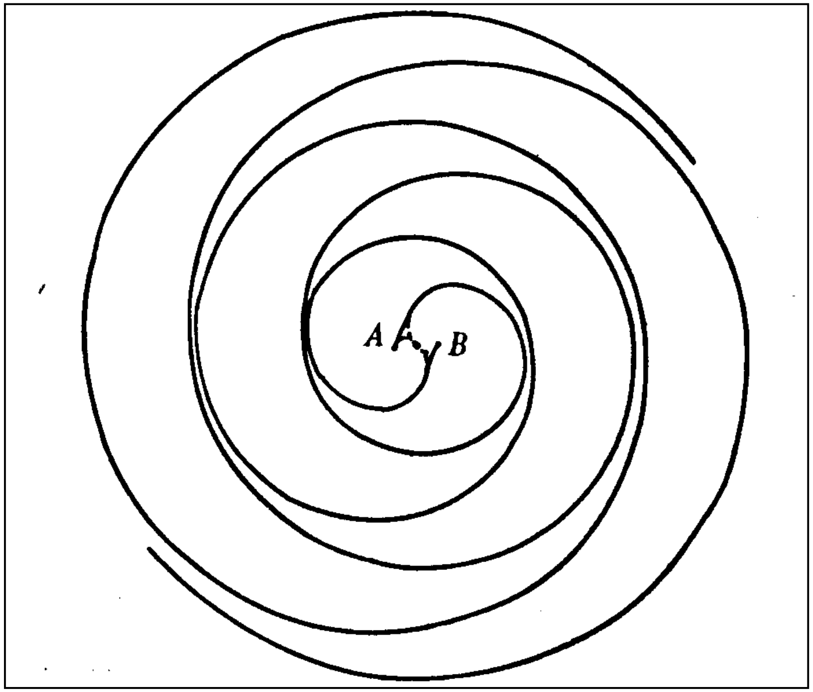


**$L < r_{crit}$**

# Two dislocation of the same sign



$L > r_{crit}$



$L < r_{crit}$

# Multiple dislocations of the same sign