

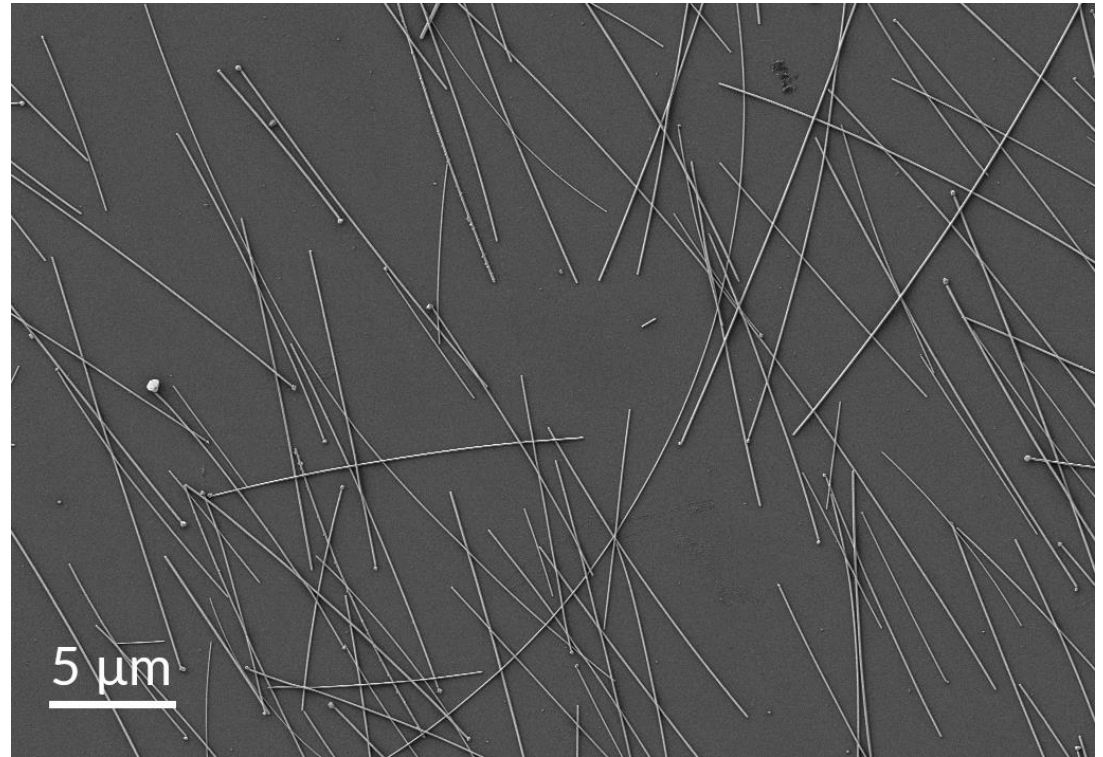
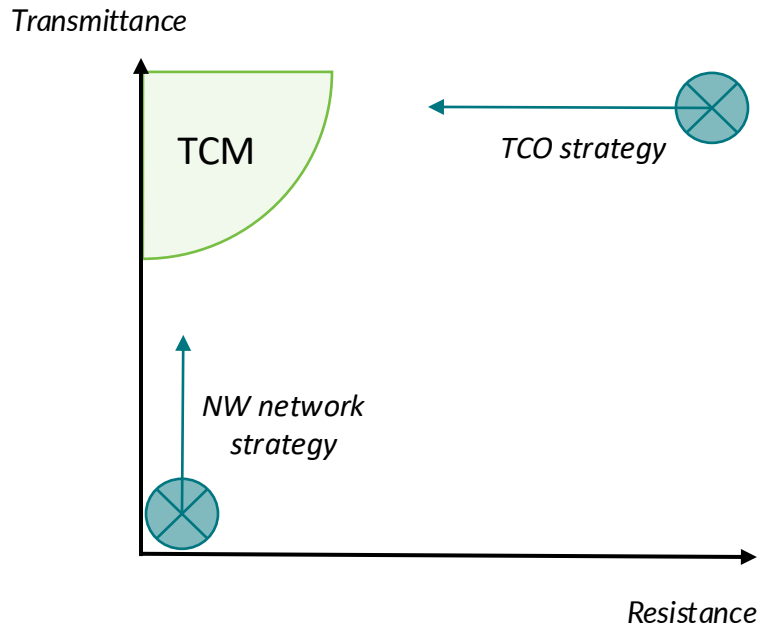
Insight into the morphological instability of metallic nanowire under thermal stress

F. Balty ^{1,2}, A. Baret ¹, A. V. Silhanek ², N. D. Nguyen ¹

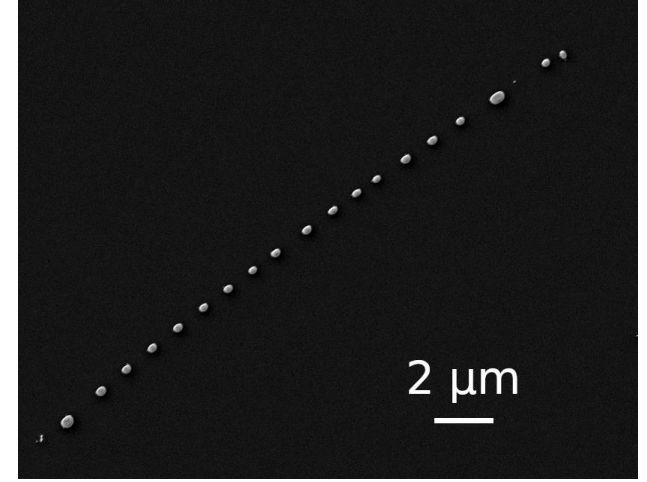
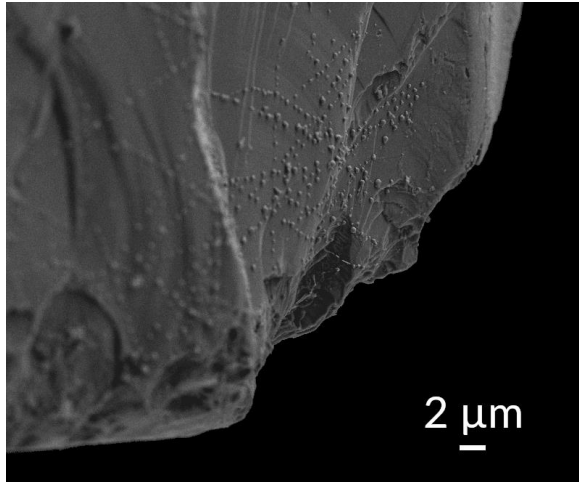
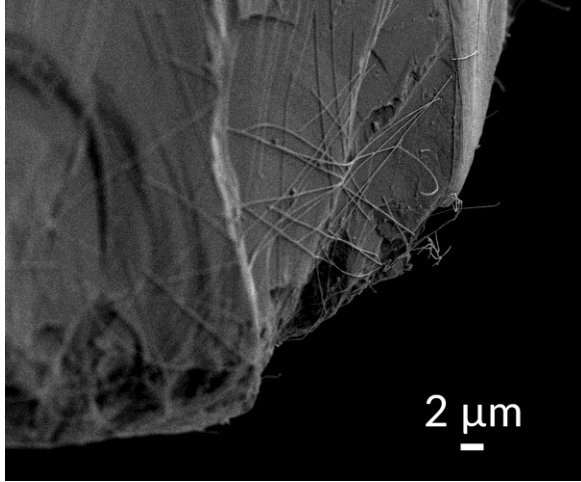
¹ SPIN – Solid state Physics of Interfaces and Nanostructures

² EPNM – Experimental Physics of Nanostructured Materials

Metallic nanowire networks as TCMs



Stability concern – spheroidization



Heating ($\sim 300 - 350\text{ }^{\circ}\text{C}$)

(Melting temperature of bulk silver : $962\text{ }^{\circ}\text{C}$)

Morphological instability - Some major contributions ...

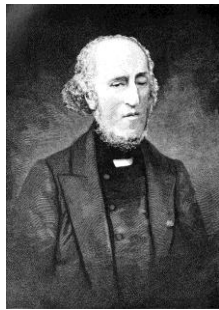
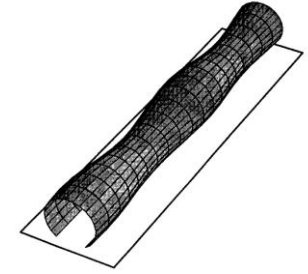
« Statique expérimentale et théorique
des liquides soumis aux seules forces
moléculaires »

J. Plateau, **1873**. [1]

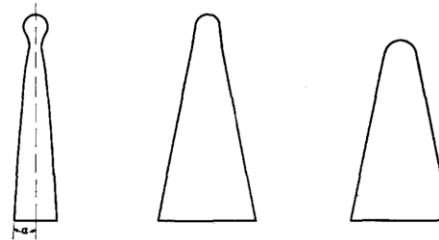


« Morphological changes of a Surface of
Revolution due to Capillarity-Induced
Surface Diffusion »

F. A. Nichols ; W. W. Mullins, **1965**. [3]



« On the instability of Jets»
Lord Rayleigh, **1878**. [2]



« Capillary instabilities in solid thin films:
Lines»

M.S. McCallum ; P. W. Voorhees ;
M. J. Miksis ; S. H. Davis ; H. Wong, **1996**.
[4]

Which theoretical model should we use ?

Plateau-Rayleigh instability [1,2]

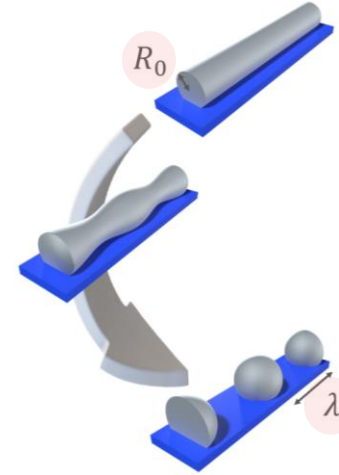


Widely accepted in literature [5 – 19]

Free standing liquid cylinder

$$\lambda \simeq 9.016 R_0$$

McCallum et al. [4]



Solid cylinder on a substrate

Mass transport = surface diffusion

$$\lambda \simeq 10.322 R_0$$

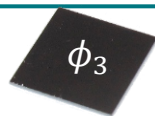
Experiments



4 solutions,
4 mean diameter



Spin coating



4 samples



SEM imaging,
100 image/sample

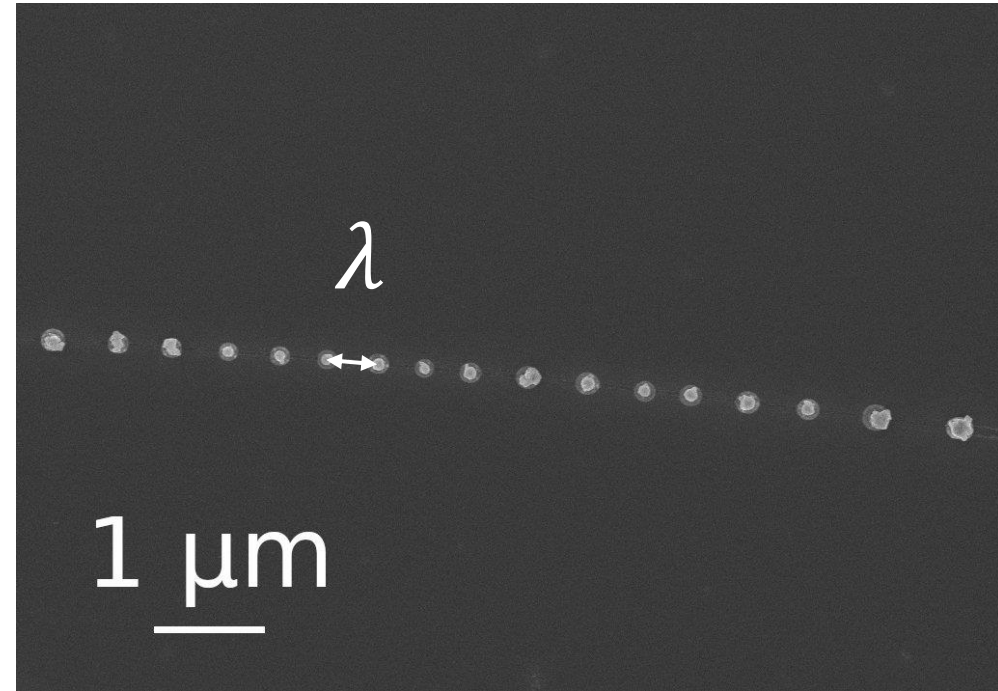
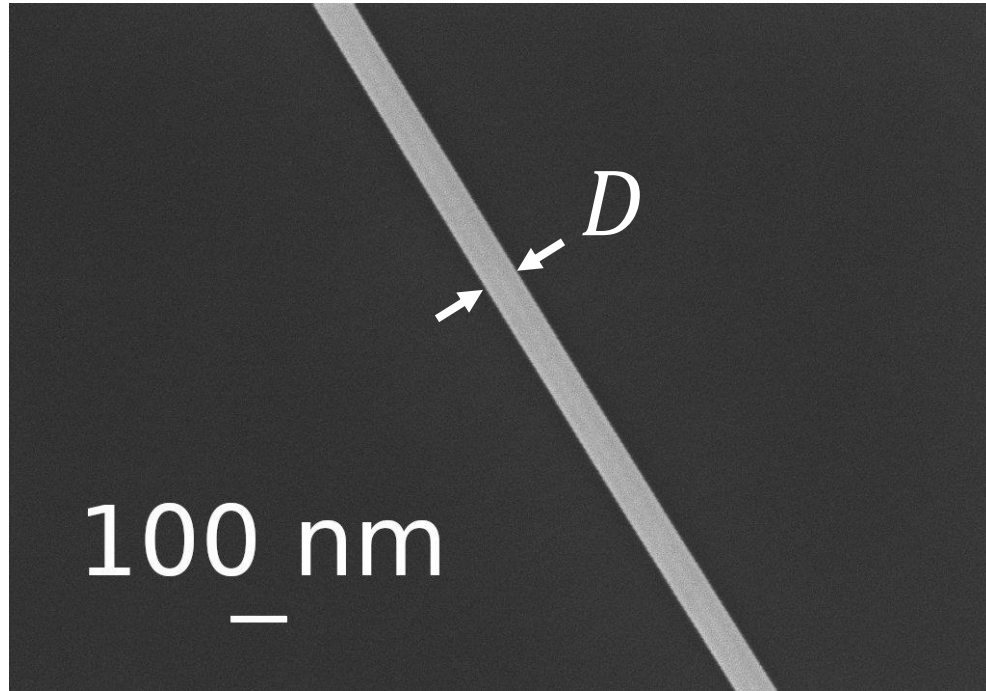


Baking

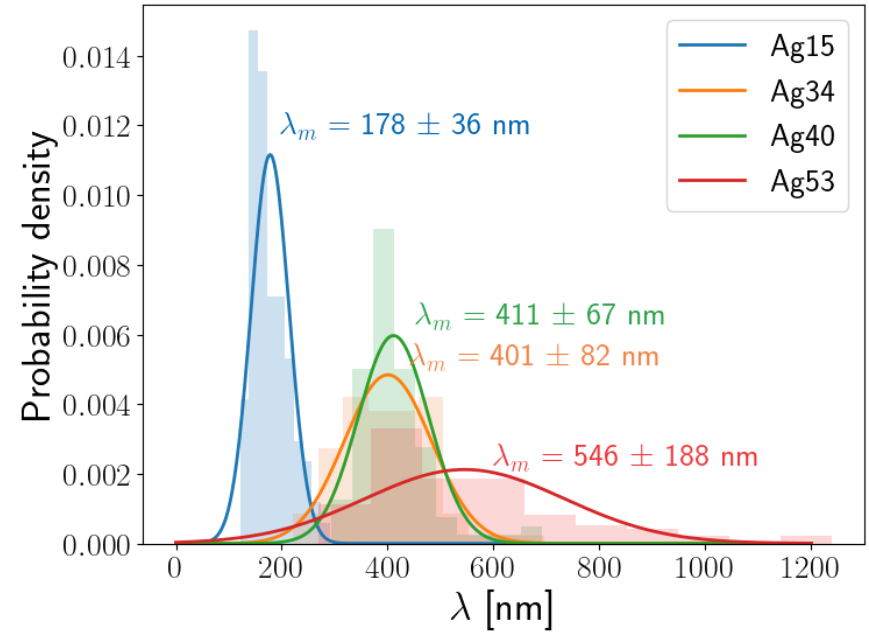
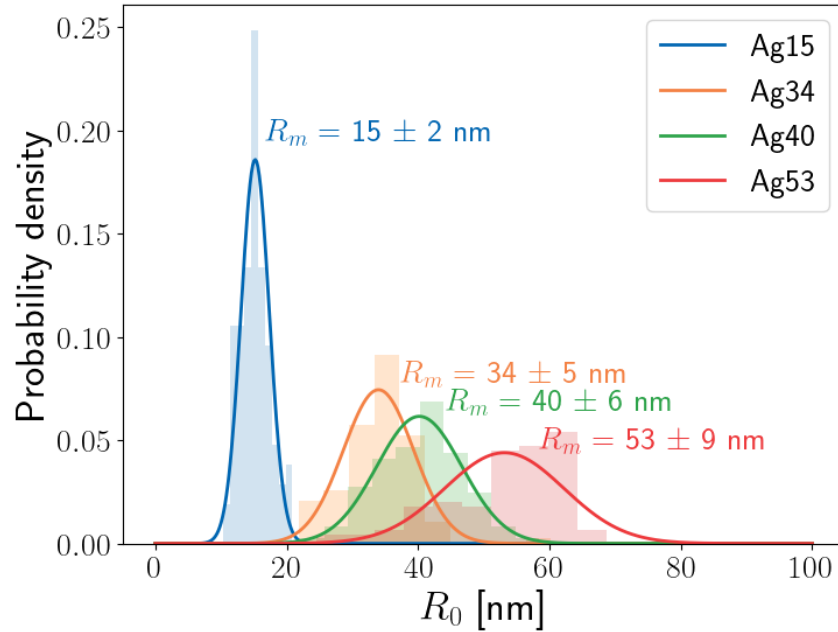


SEM imaging,
100 image/sample

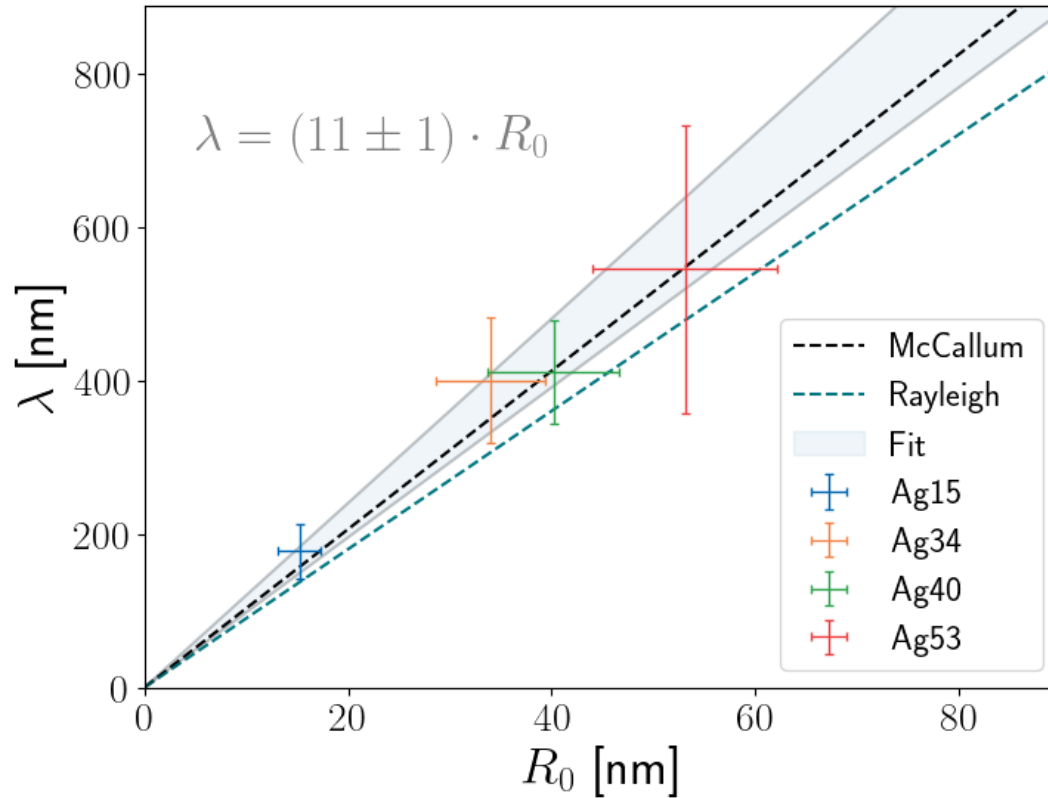
Data treatment



Results — statistical distributions



Results – Model comparison

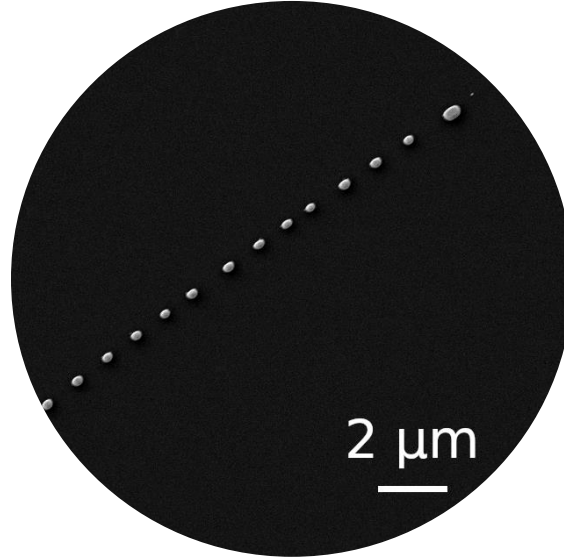


- Rayleigh : $\lambda \simeq 9.016 R_0$,
- McCallum et al. : $\lambda \simeq 10.322 R_0$,
- Experiments : $\lambda = (11 \pm 1) R_0$.

Conclusions



« Plateau-Rayleigh » terminology to describe the thermal instability of metallic NWs is misleading.

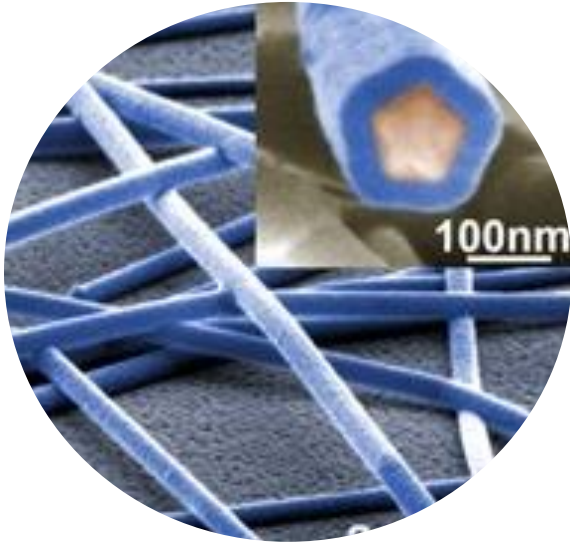


The model of McCallum et al. provide a more accurate description.

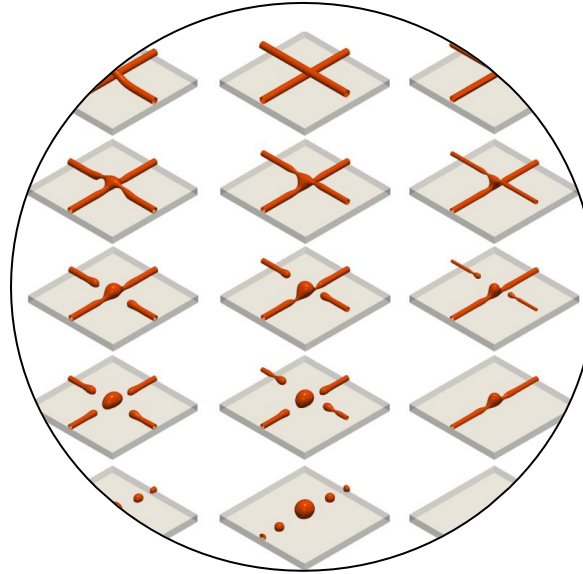


No threshold temperature for instability, accelerated with increased atom mobility.

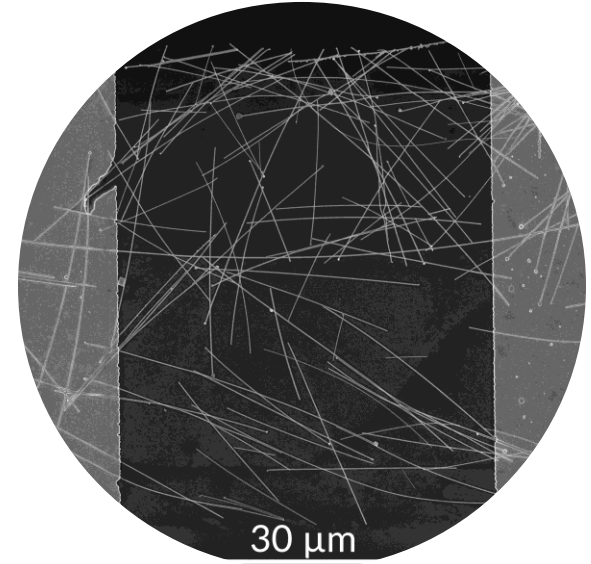
Perspectives



McCallum model gives a theoretical framework for stability improvement [16]



Improved theoretical model through simulations



Coupled instability, such as electrical stresses

For more information ...



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Regular Article

Insight into the morphological instability of metallic nanowires under thermal stress

François Balty ^{a, b} , Amaury Baret ^a , Alejandro Silhanek ^b , Ngoc Duy Nguyen ^a 

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More from SPIN :

A. Baret – Tuesday @ 18:30, Room Achilles



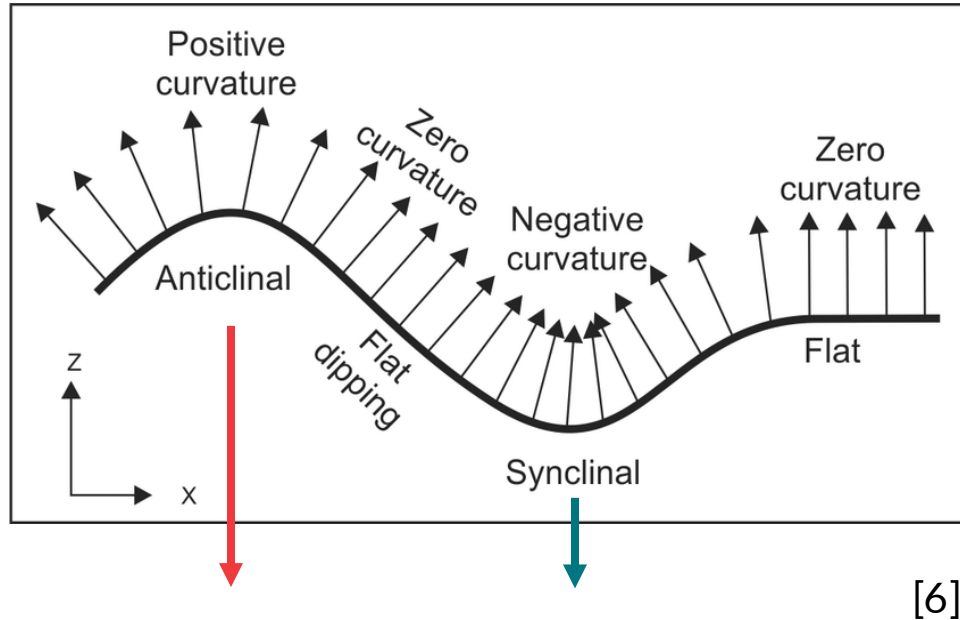
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20. F. Balty et al., *Journal of Colloid and Interface Science* **673**, 574-582 (2024).

Surface diffusion as mass transport



High μ

Low μ

- We can show :

$$\mu = \kappa \Omega \gamma$$

Where :

- μ = chemical potential
- κ = curvature
- Ω = atomic volume
- γ = interfacial energy

→ Gradient of chemical potential = driving force of diffusion !

McCallum et al. Framework – Equation of motion

- Surface flux = # atoms per unit wire area * drift velocity, $J = n_0 v_d$
- Drift velocity = mobility * driving force, $v_d = B F = -\frac{D_s}{k_B T} \nabla \mu = -\frac{D_s}{k_B T} \nabla(\kappa \Omega \gamma)$
- The **interface evolution over time** is described by the local speed of surface elements perpendicular to the interface, which can be written as $\Omega \nabla_s \cdot J$.

Combining those equation, we have :

$$\Omega \nabla_s \cdot J = -\frac{D_s \gamma \Omega^2 n_0}{k_B T} \nabla_s^2 \kappa$$

- Which can be expressed as a function of the vector normal to an interface u_n as :

$$R_t \cdot u_n = -\frac{D_s \gamma \Omega^2 n_0}{k_B T} \nabla_s^2 (\nabla \cdot u_n)$$

McCallum et al. Framework – Studied situation

- Equation : $\mathbf{R}_t \cdot \mathbf{u}_n = - \frac{D_s \gamma \Omega^2 n_0}{k_B T} \nabla_s^2 (\nabla \cdot \mathbf{u}_n)$

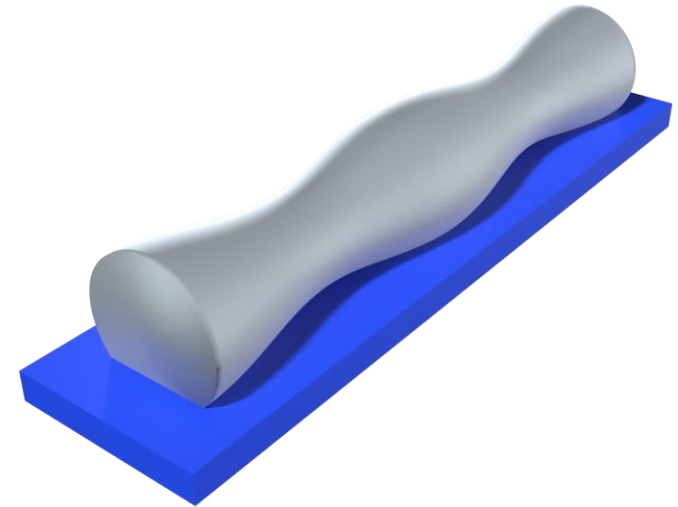
- Considered interface :

$$r(t, \theta, y) = R_0 + \epsilon r^\Delta e^{iky + \sigma t}$$

- With :

- $\epsilon \ll R_0$
- r^Δ = a function of θ

- We suppose a constant contact angle α



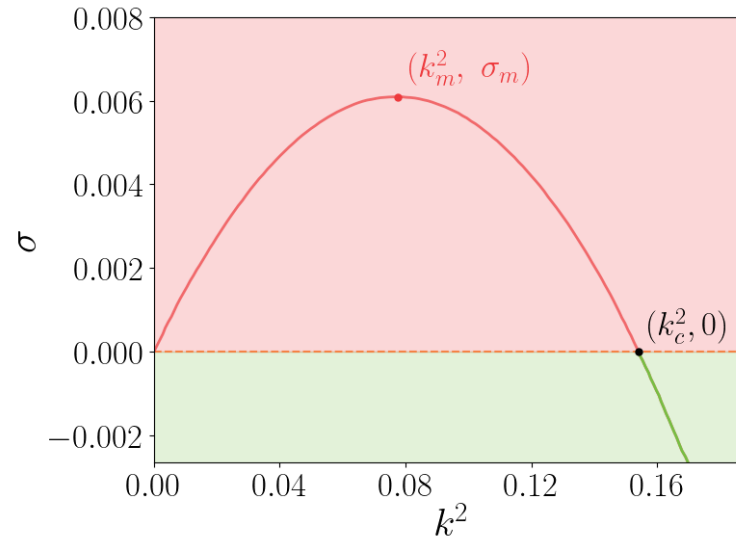
→ Periodical perturbation

→ Can increase or decrease over time

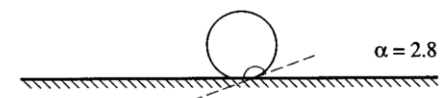
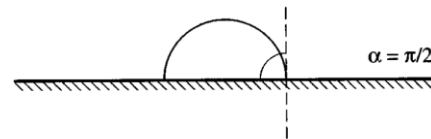
McCallum et al. framework — Results

- The final solution is a functional constraint which must be satisfied by the three parameters α , k and σ .

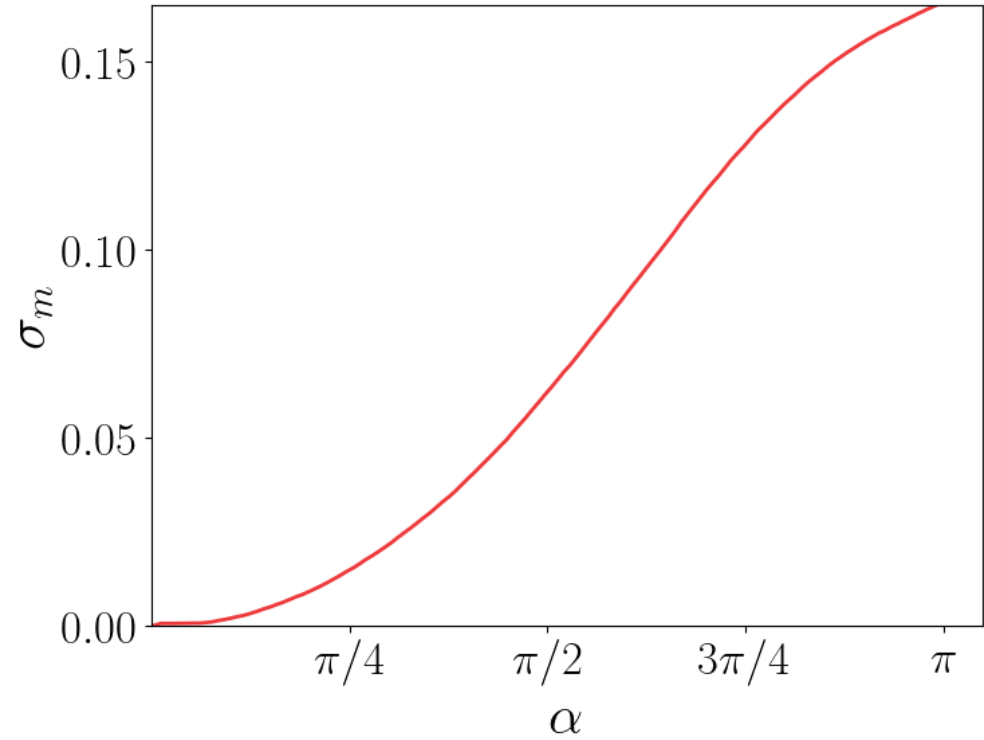
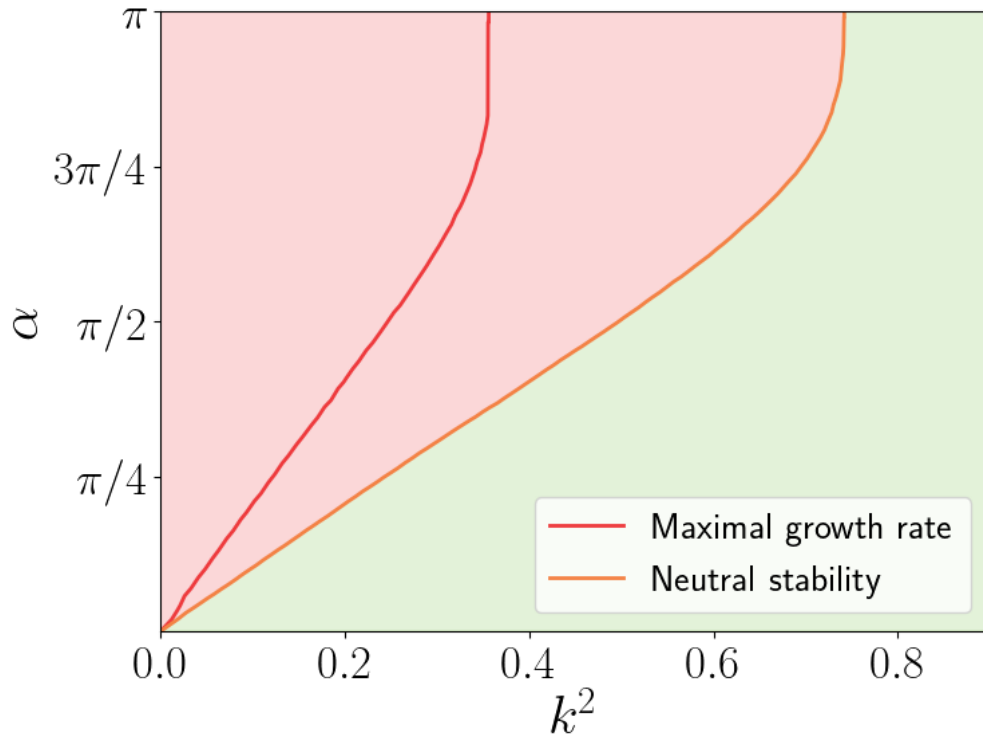
- For a given contact angle $\alpha = 0.5$:



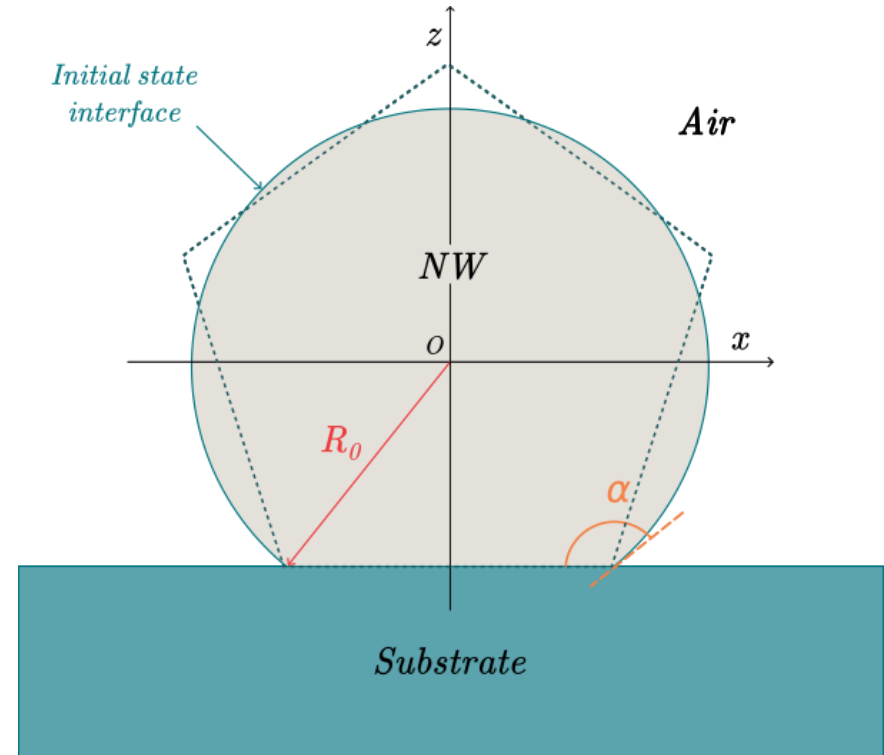
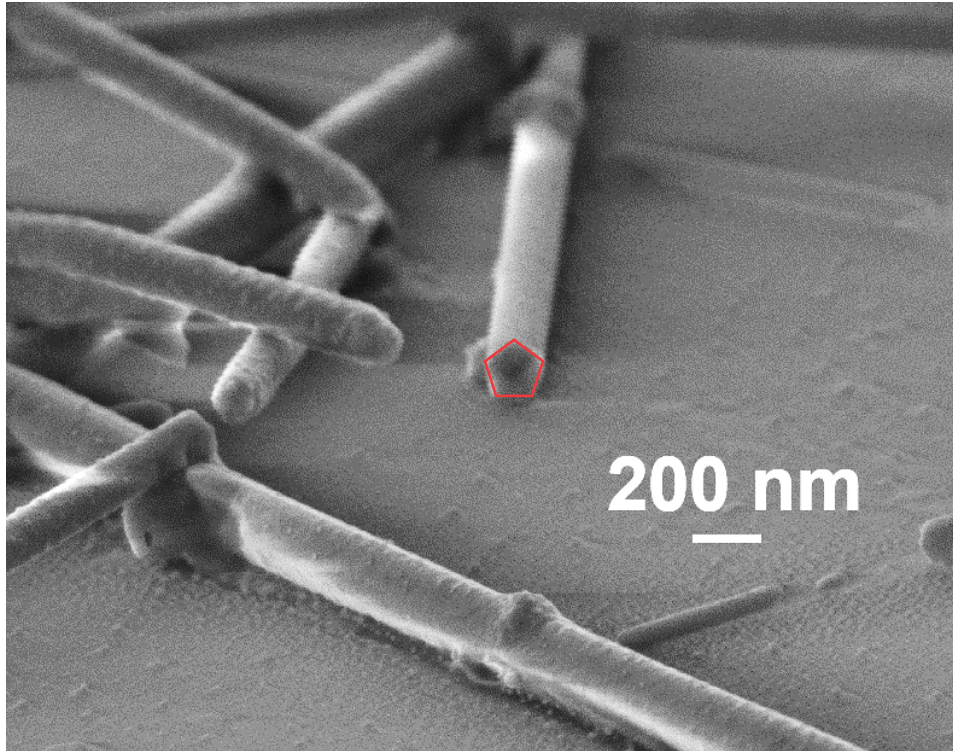
- What about other contact angles ?



McCallum et al. framework — Results

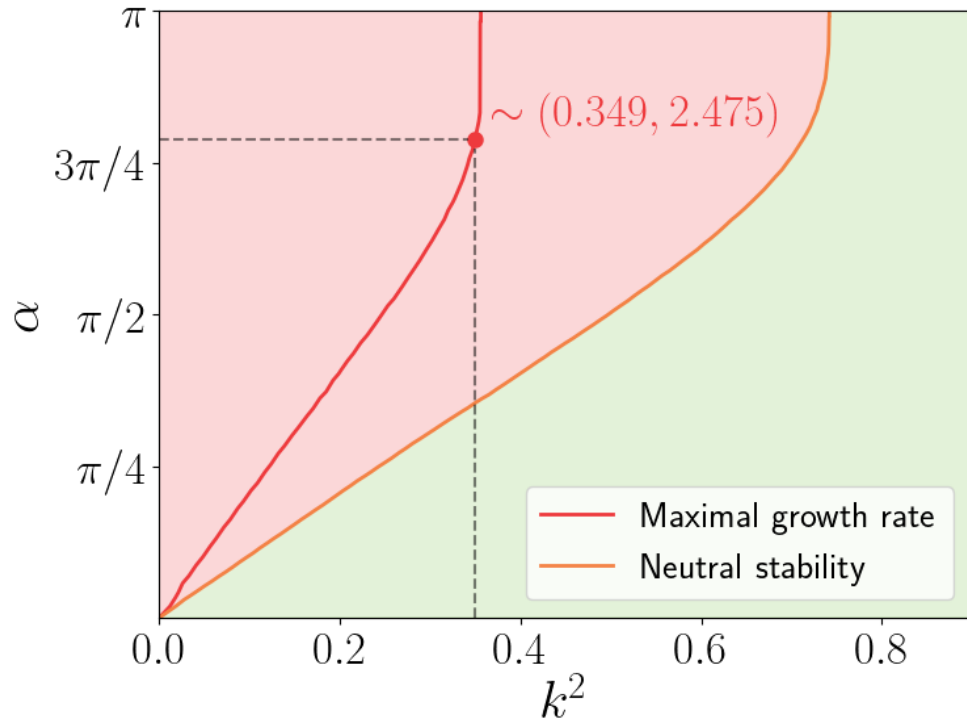


Case of polyol-grown silver nanowire



$$\Rightarrow \alpha \simeq 2.475 \simeq 142^\circ$$

Case of polyol-grown silver nanowire



- Adimensional analysis,
- Unit length : $L = R_0 \sqrt{\frac{\alpha - \sin(\alpha) \cos(\alpha)}{\pi}},$
- Dimensional wavenumber : $k = \frac{\tilde{k}}{L} \left(= \frac{2\pi}{\lambda} \right).$

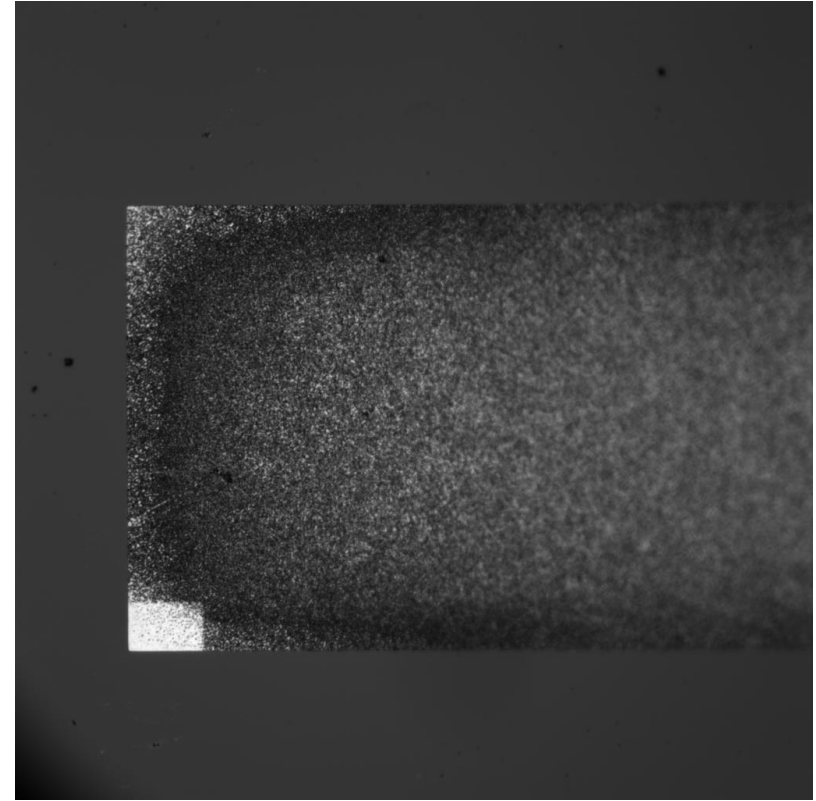
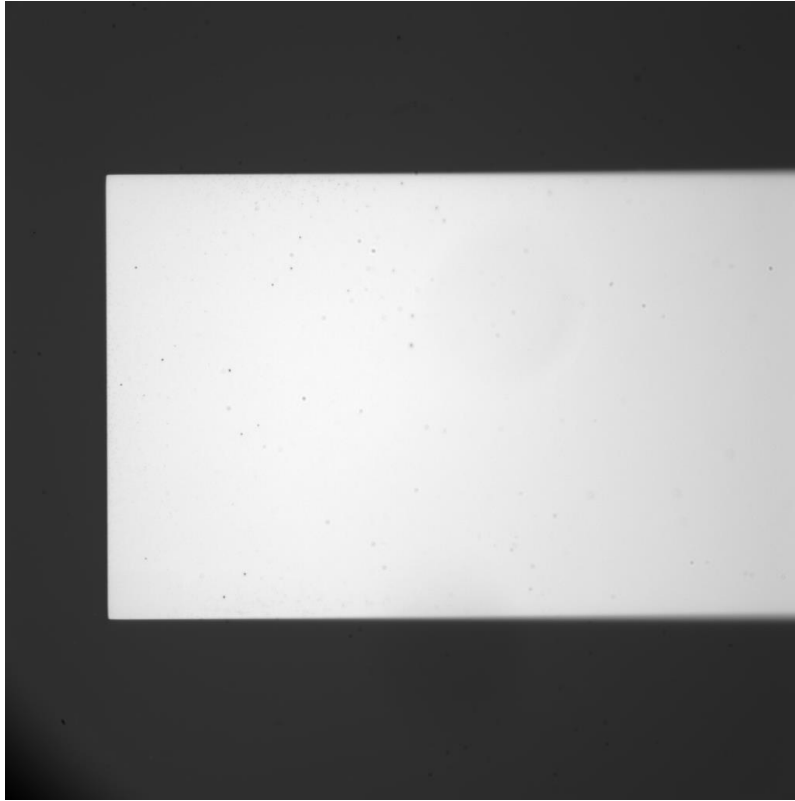
$$\Leftrightarrow \lambda = \frac{2\pi L}{\tilde{k}}$$

$$= \frac{2\pi \sqrt{\frac{\alpha - \sin(\alpha) \cos(\alpha)}{\pi}} R_0}{\tilde{k}}$$

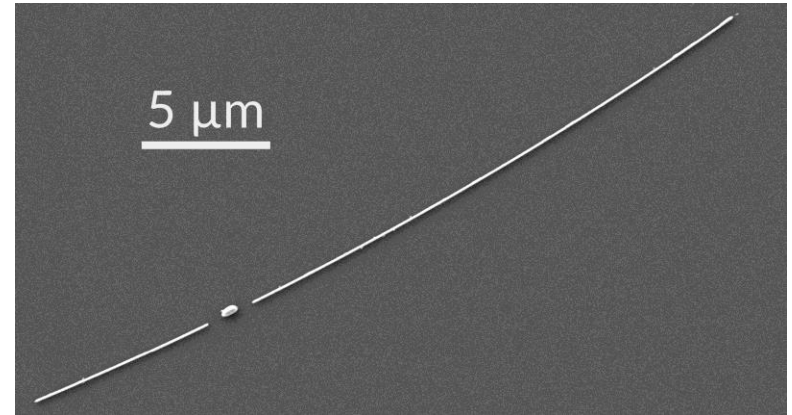
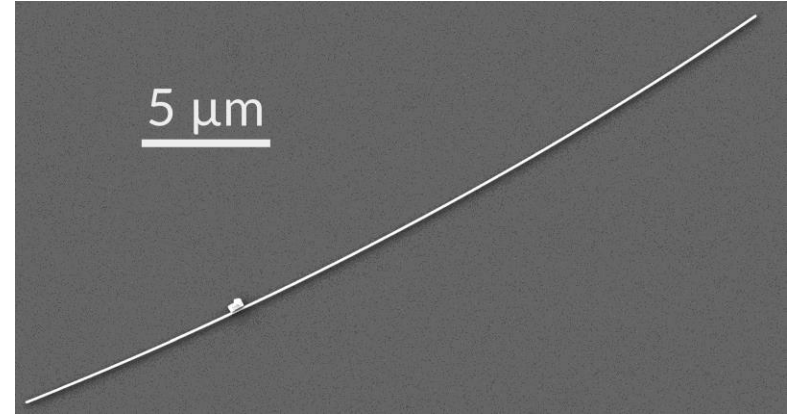
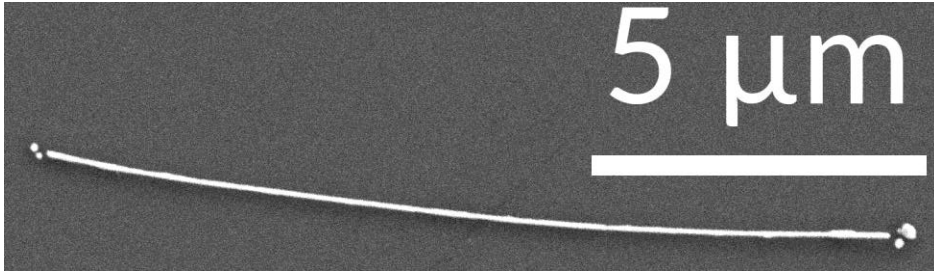
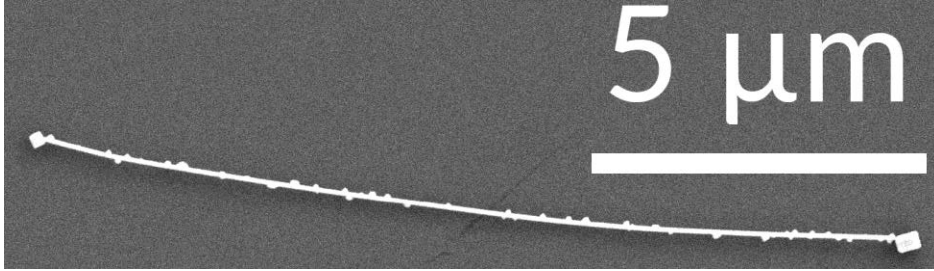
$\Rightarrow$

$$\lambda \simeq 10.322 R_0$$

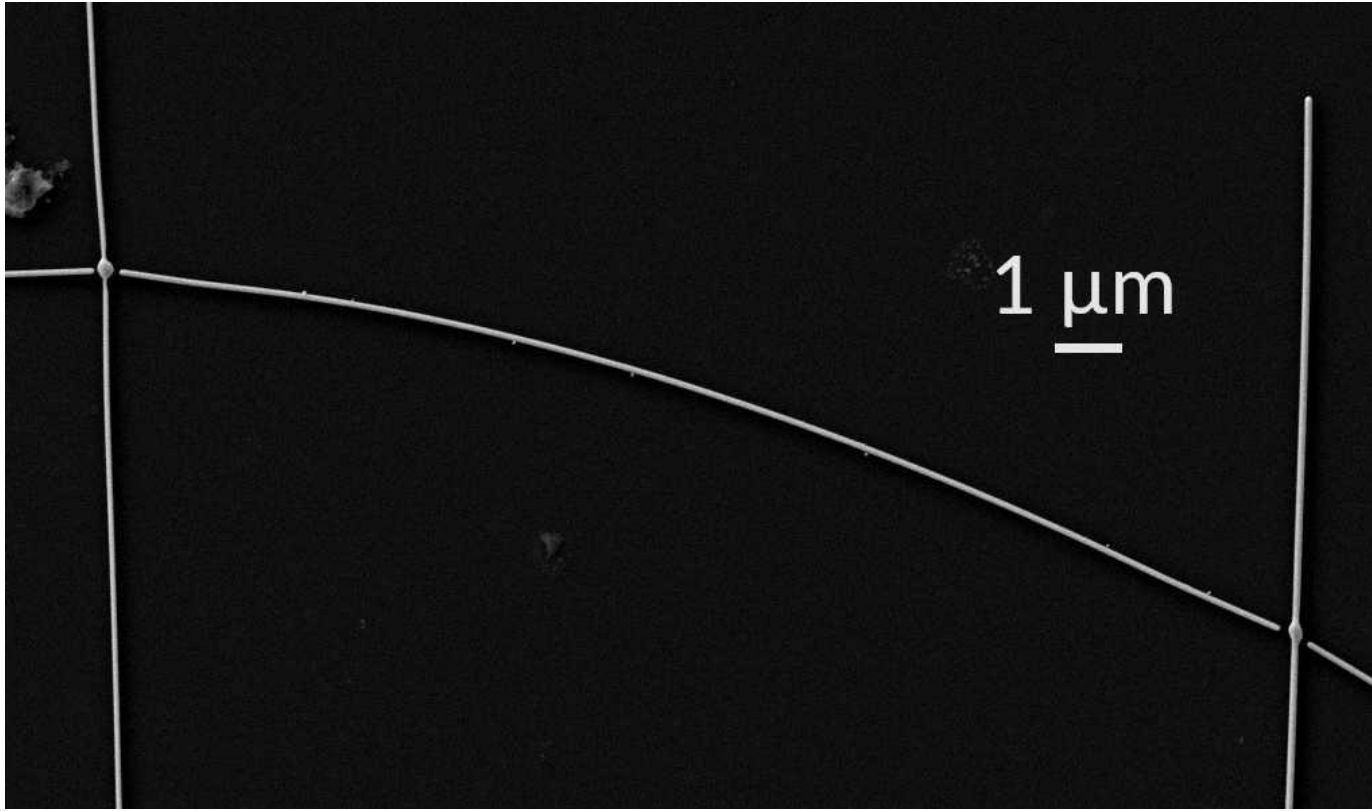
Experimental verification – technical challenge



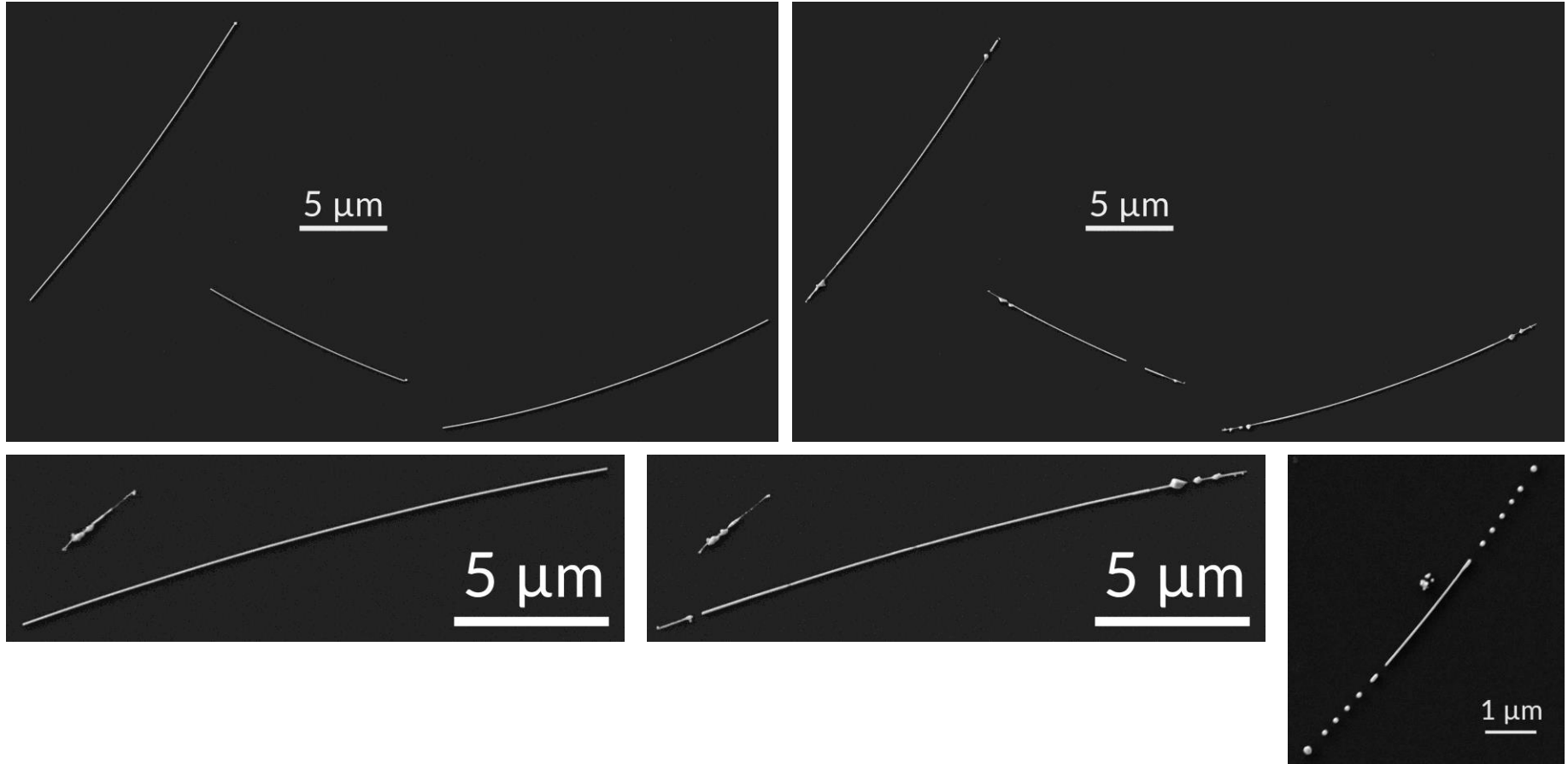
Perspectives – Aperiodic defects



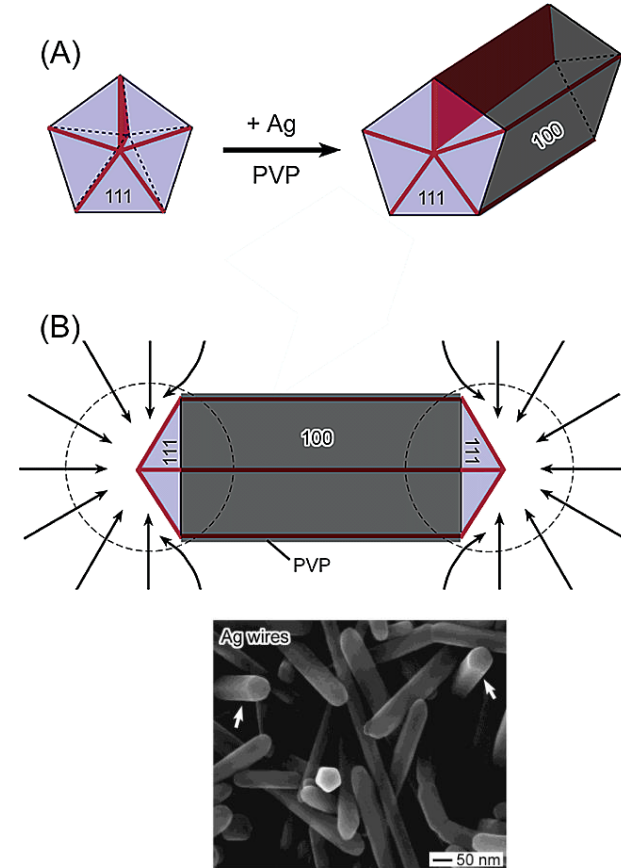
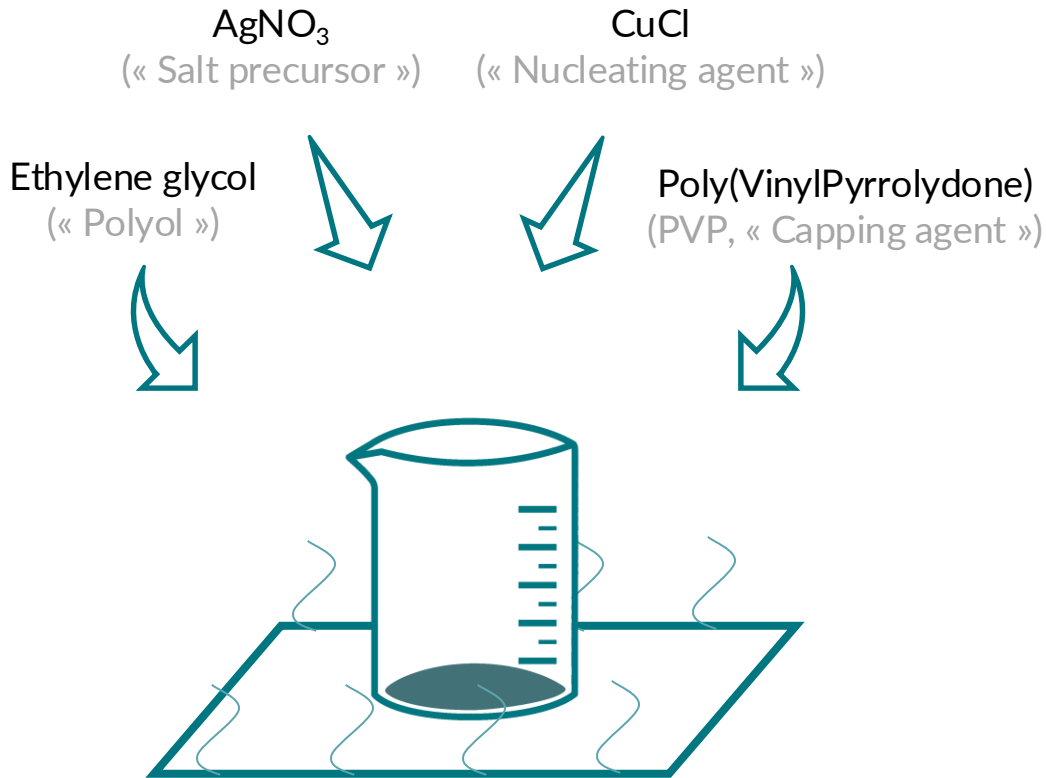
Perspectives – Case of junctions



Perspectives – Edges



Growth of AgNWs – Polyol process



[1]