Silver Droplets Resulting from Morphological Instabilities of Silver Nanowires below the Bulk Melting Point

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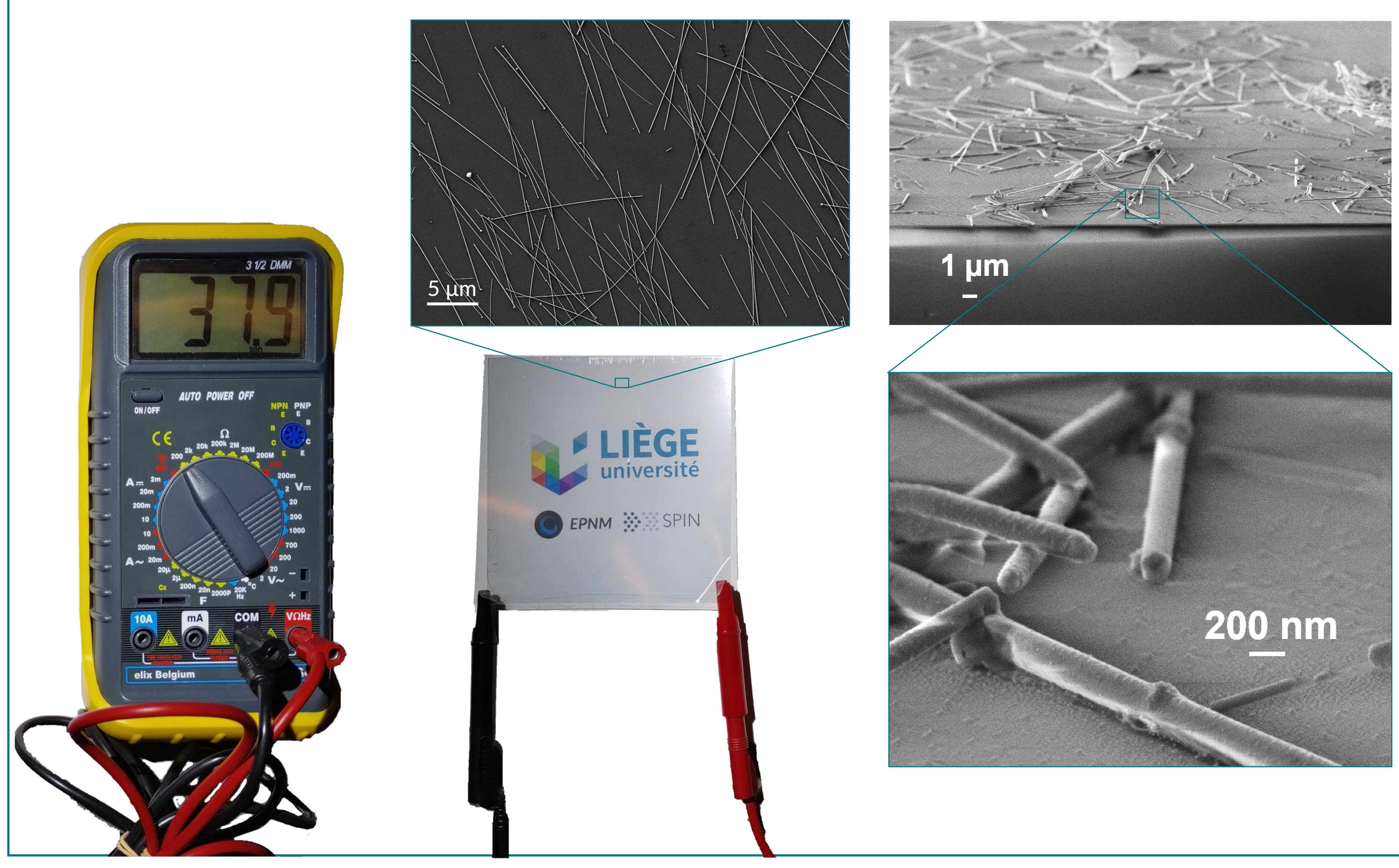
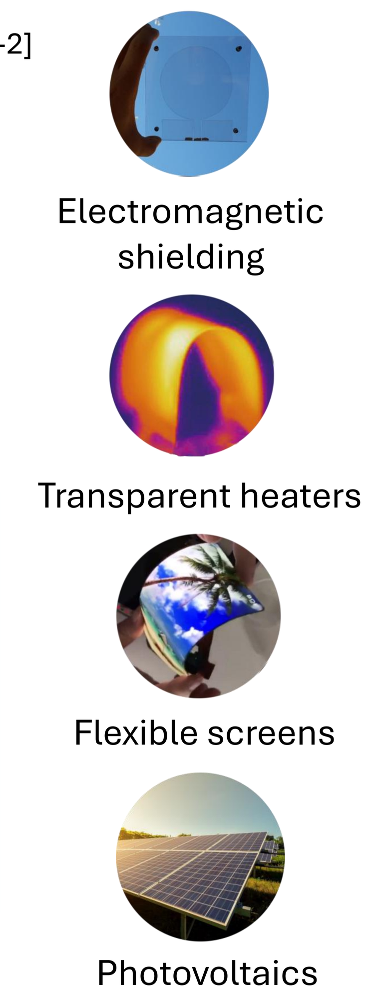
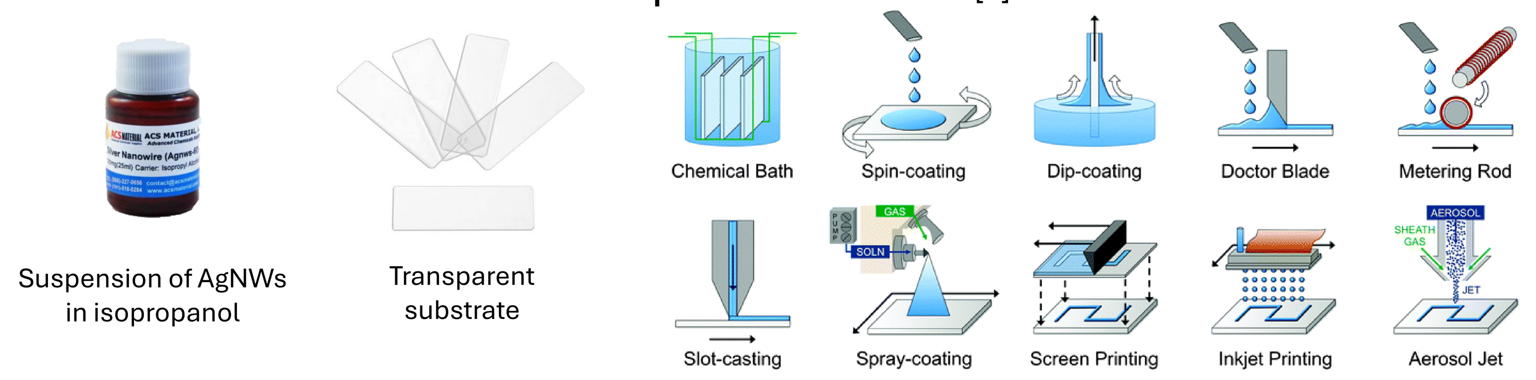
Context

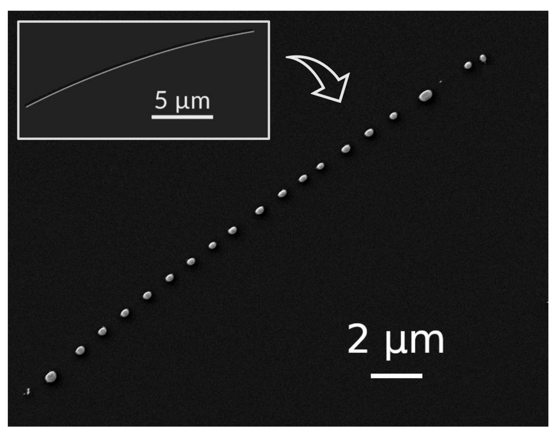
Silver nanowire as Transparent Conducting Material [1-2]





Sample fabrication [3]



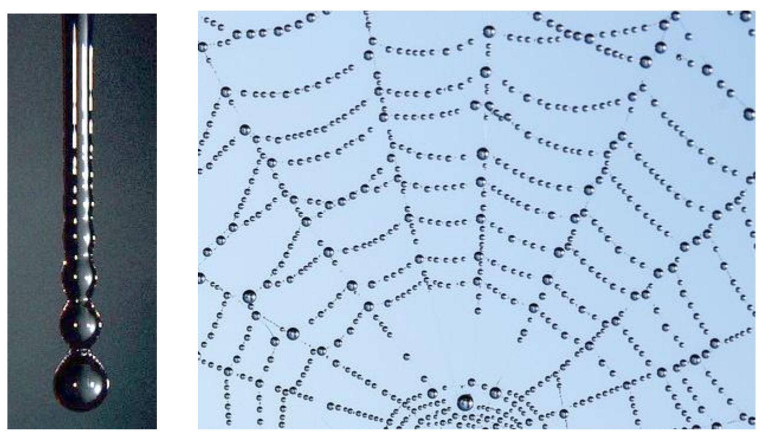


Spheroidization

- Heating at around 300 – 350 °C (melting point of bulk silver 962 °C)
- **Prevents** the use of silver nanowires in devices requiring **high-temperature annealing** manufacturing steps
- Observed for other metallic nanowires [4-8]

Theory

Rayleigh [9]



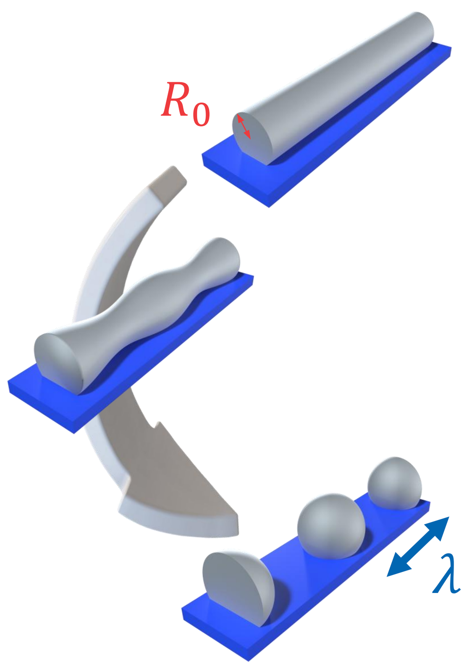
- Widely accepted in literature
- **Free-standing liquid** cylinder
- Mass transport : liquid **flow**
- Prediction :

$$\boxed{\lambda \simeq 9.016\, R_0}$$

where :

- λ is the wavelength of the instability
- R_0 is the initial radius of the cylinder

McCallum et al. [10]



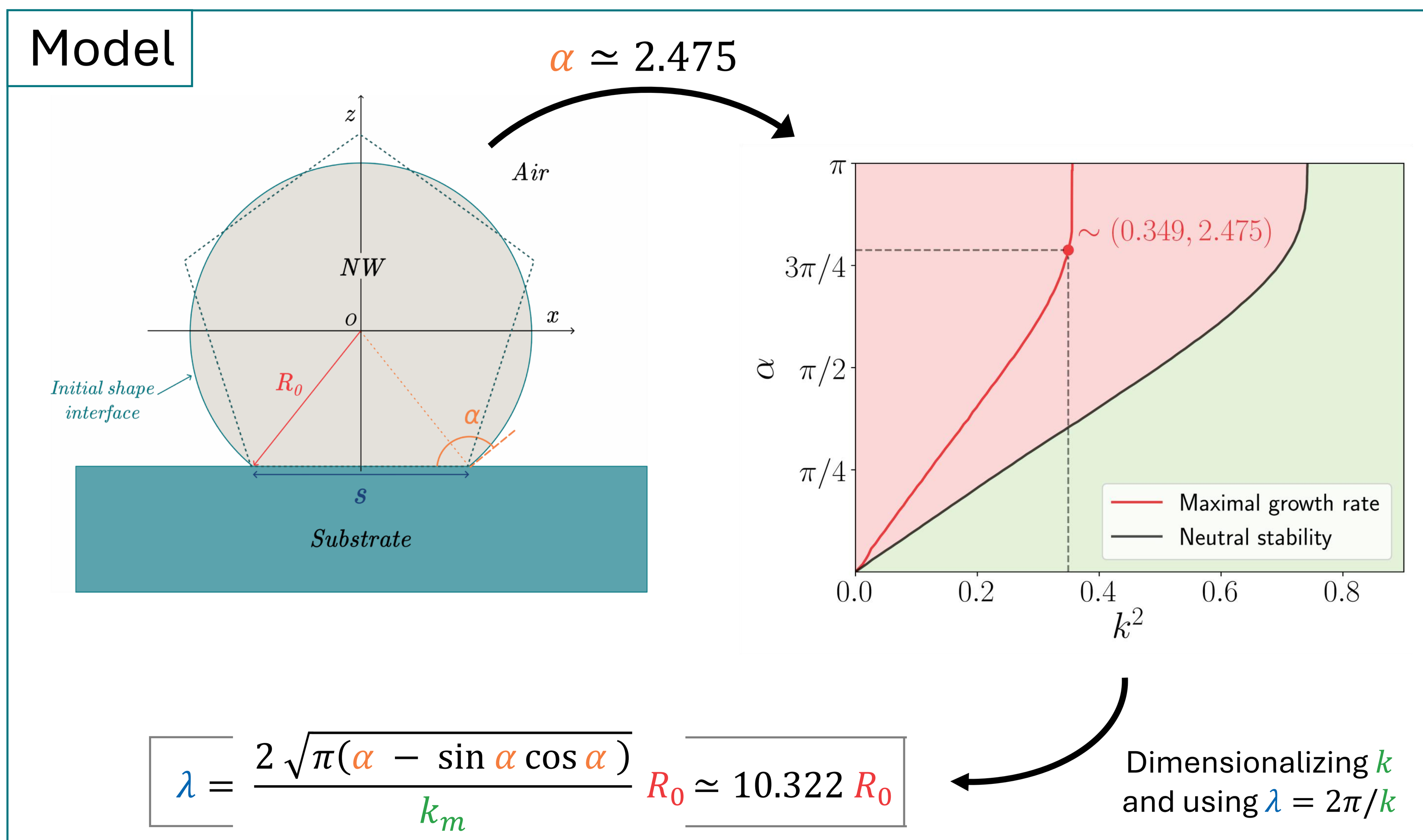
- **Solid** cylinder **on a substrate**
- Mass transport : surface **diffusion**
- Prediction :

For an interface described by

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

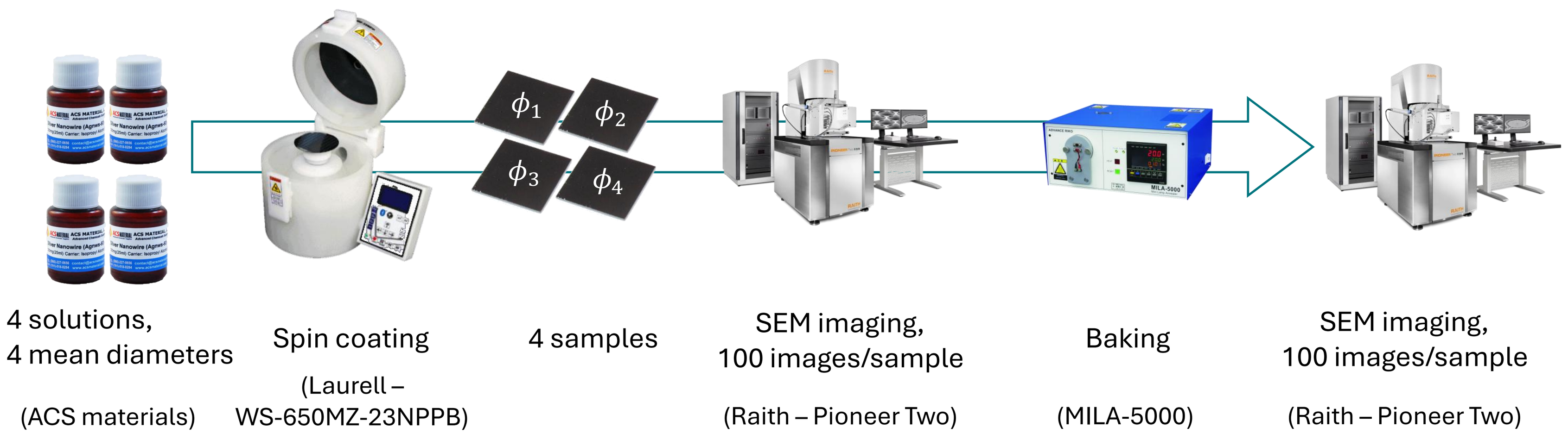
There exists a relationship $\sigma = \sigma(k,\alpha)$ from which the linear relationship between λ and R_0 can be extracted.

Model

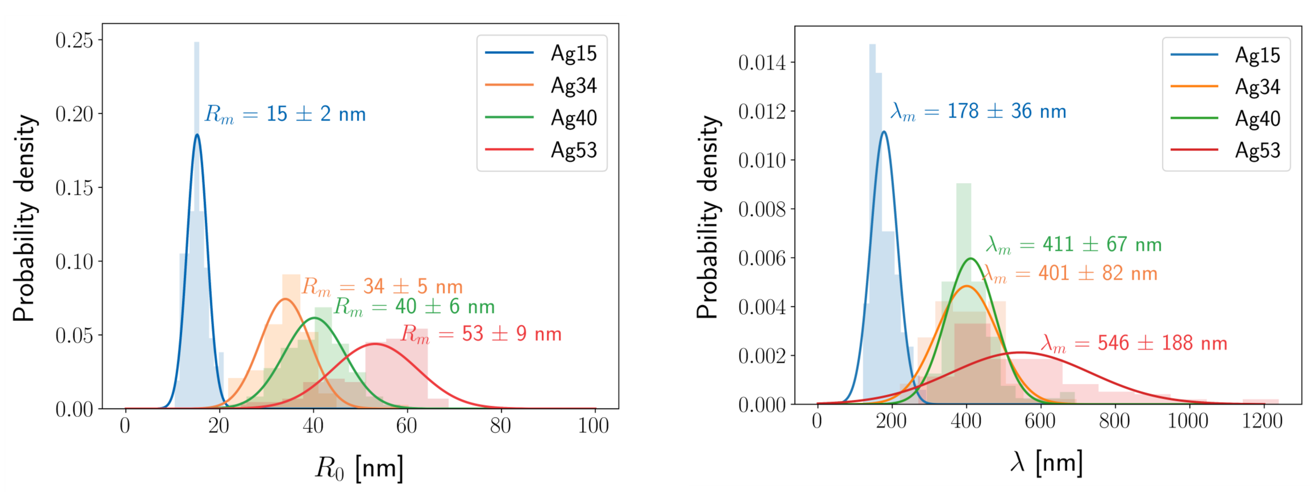


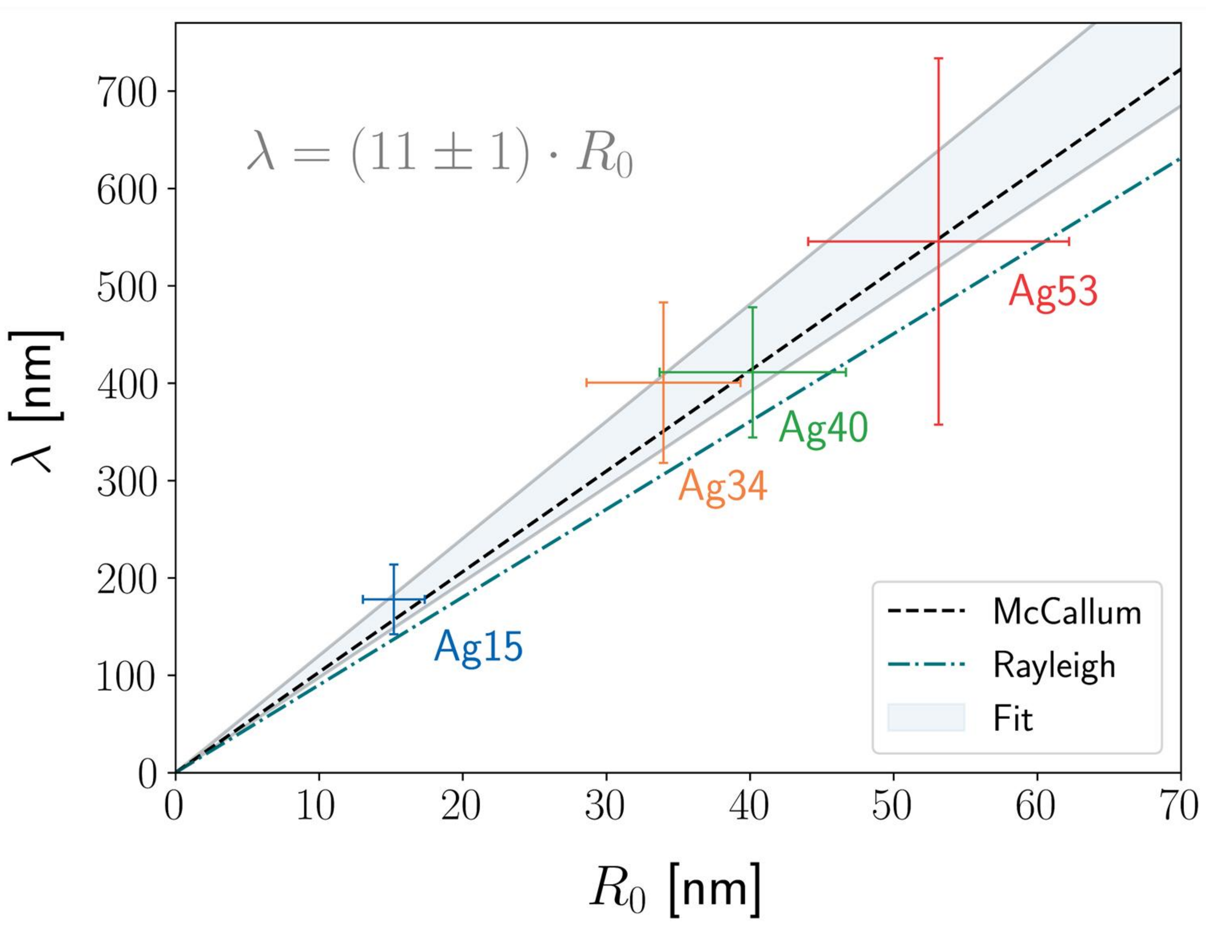
$$\boxed{\lambda = \frac{2\sqrt{\pi(\alpha - \sin\alpha\cos\alpha)}}{k_m} R_0 \simeq 10.322\, R_0}$$

Experiments



Results and discussion





Stability is enhanced by decreasing the growth rate :

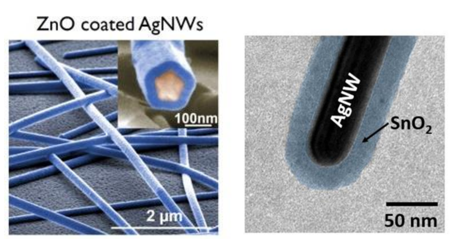
$$\sigma = \pi^2 \frac{\tilde{\sigma}\, D_s\, \gamma\, \Omega^2\, n_0}{k_B\, T\, (\alpha - \sin\alpha\cos\alpha)^2\, R_0^4}$$

with :

Symbol	Physical property	Unit
$\tilde{\sigma}$	Adimensional growth rate	/
D_s	Surface diffusivity	$m^2\,s^{-1}$
γ	Interfacial energy	$J\,m^{-2}$
Ω	Atomic volume	m^3
n_0	Number of atoms per unit area	m^{-2}
T	Temperature	K

Paths for stability enhancement :

- Annealing at lower temperatures for longer durations
  - Exponential asymptotic behaviour with T
- Favouring larger nanowires
  - Inverse quartic behaviour with the initial radius, $\sigma \propto R_0^{-4}$
- Optimizing surface coating
  - Numerical criterion for the choice of coating



[11-12]

Conclusions

- McCallum et al.'s model provides a **more accurate** description of the **spheroidization** of metallic nanowires compared to Rayleigh's model.
- This model can serve as **a theoretical framework** for the development of methods designed to enhance the stability of metallic nanowires.

References

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