Silver Nanowire Networks as Transparent Conducting Materials

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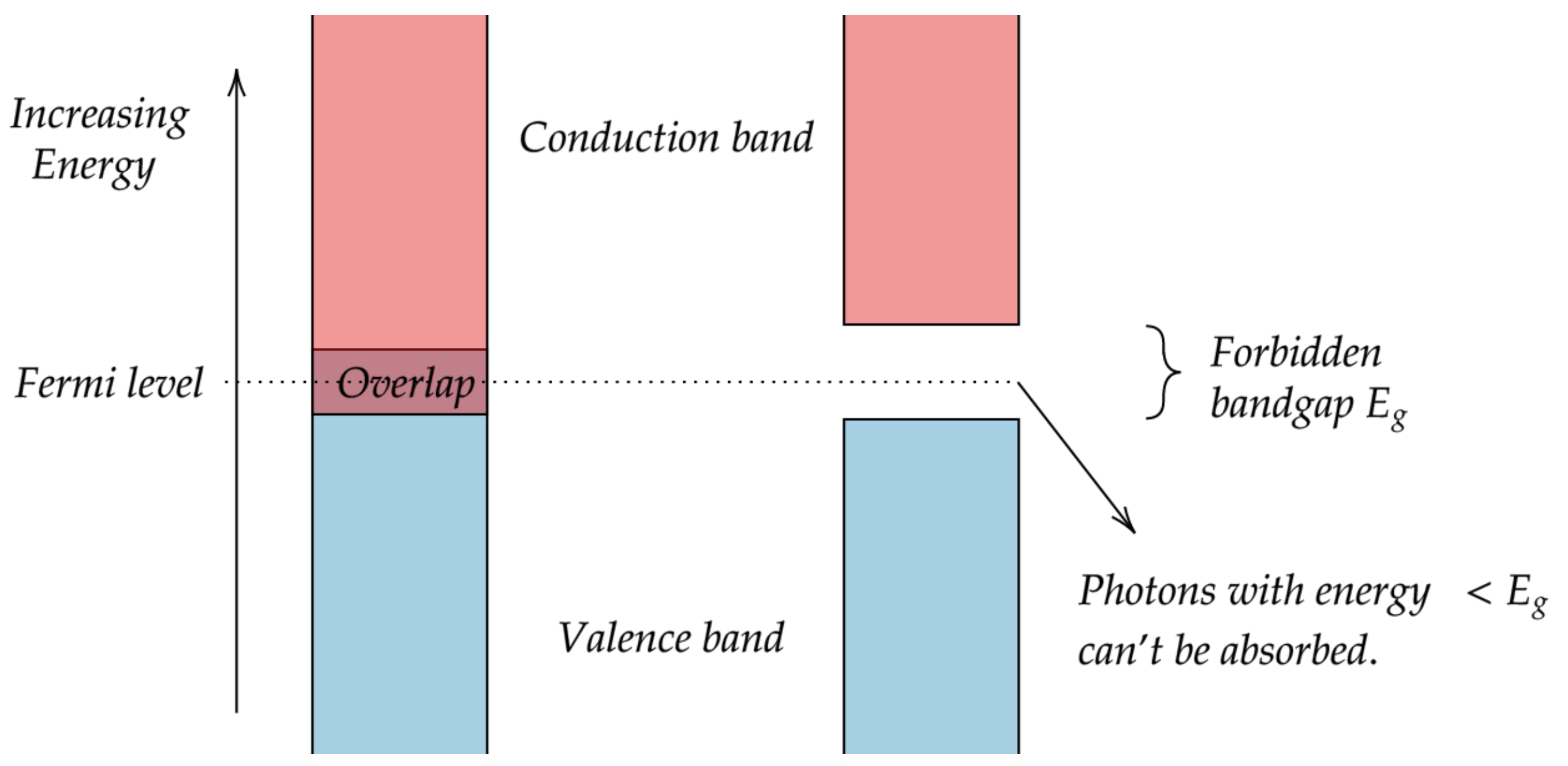
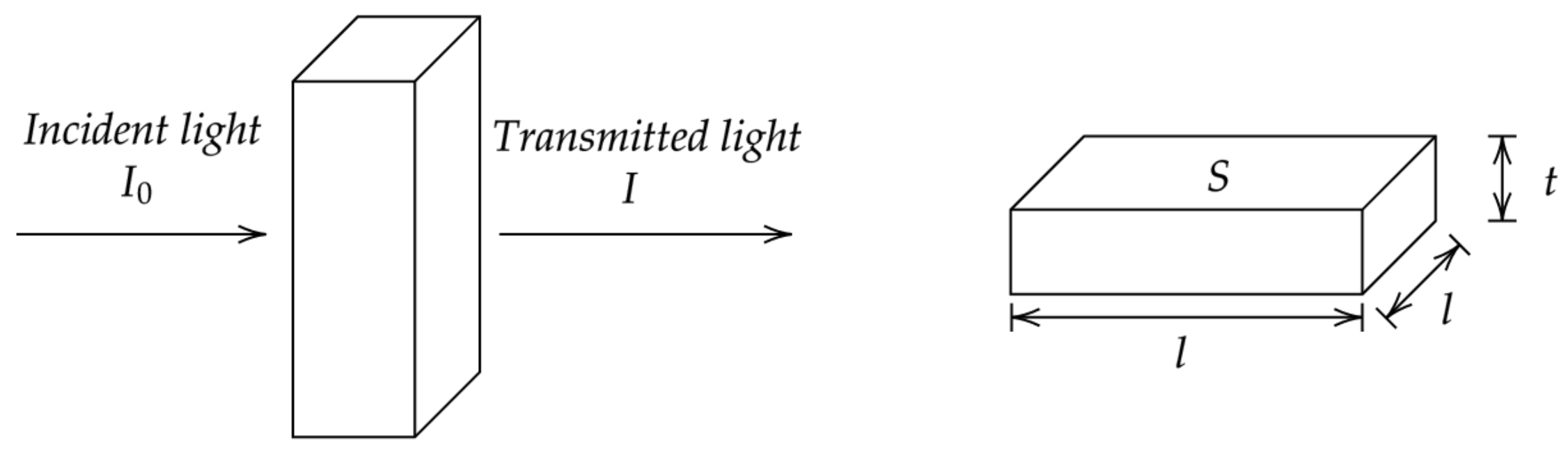
Transparent Conducting Materials (TCMs)

Transparent conducting solids combine both **optical transparency** and **electrical conductivity**. They are associated to several important applications in modern technologies such as liquid crystal displays (LCDs), organic light-emitting diodes (O-LEDs), touch screens, solar cells or transparent heaters.

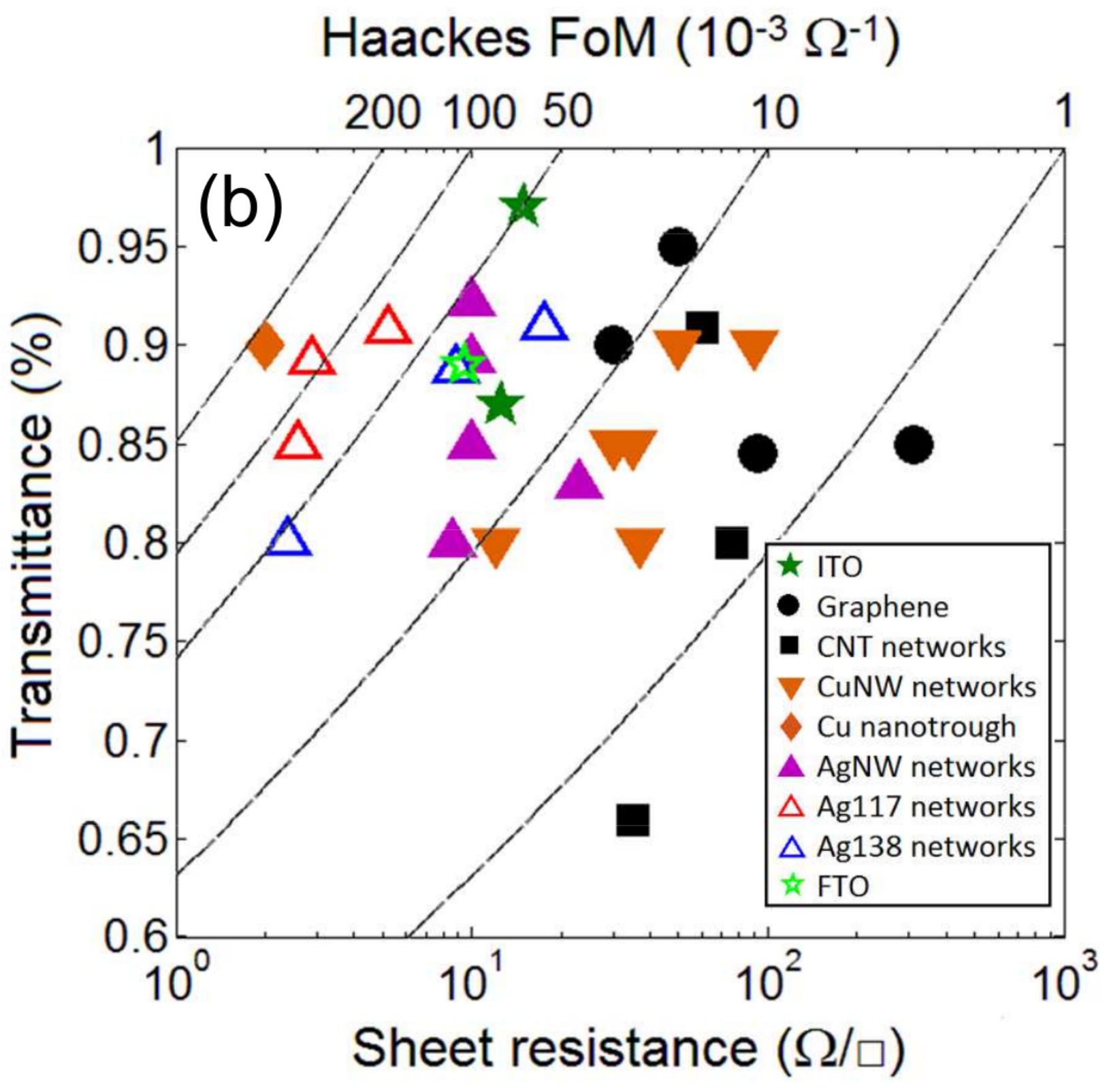
This association of properties results from a **complex process**. Indeed, band theory explains optical transparency with the large gap between the valence and conduction bands, preventing the photons to be absorbed by valence electrons. On the contrary, in the case of a conductor, those bands are overlapping, allowing to have free electrons at the Fermi level. Therefore, a combination of those properties should circumvent this apparent contradiction.





$$T = \frac{I}{I_0}$$

$$R_s = \rho \frac{l}{S} = \rho \frac{l}{l \cdot t} = \frac{\rho}{t}$$



[1]

Optical and electrical properties of solid thin films are usually quantified using respectively **Transmittance** T and **Sheet Resistance** R_s, defined in the left figure. A figure of merit has been defined by G. Haacke as [2] :

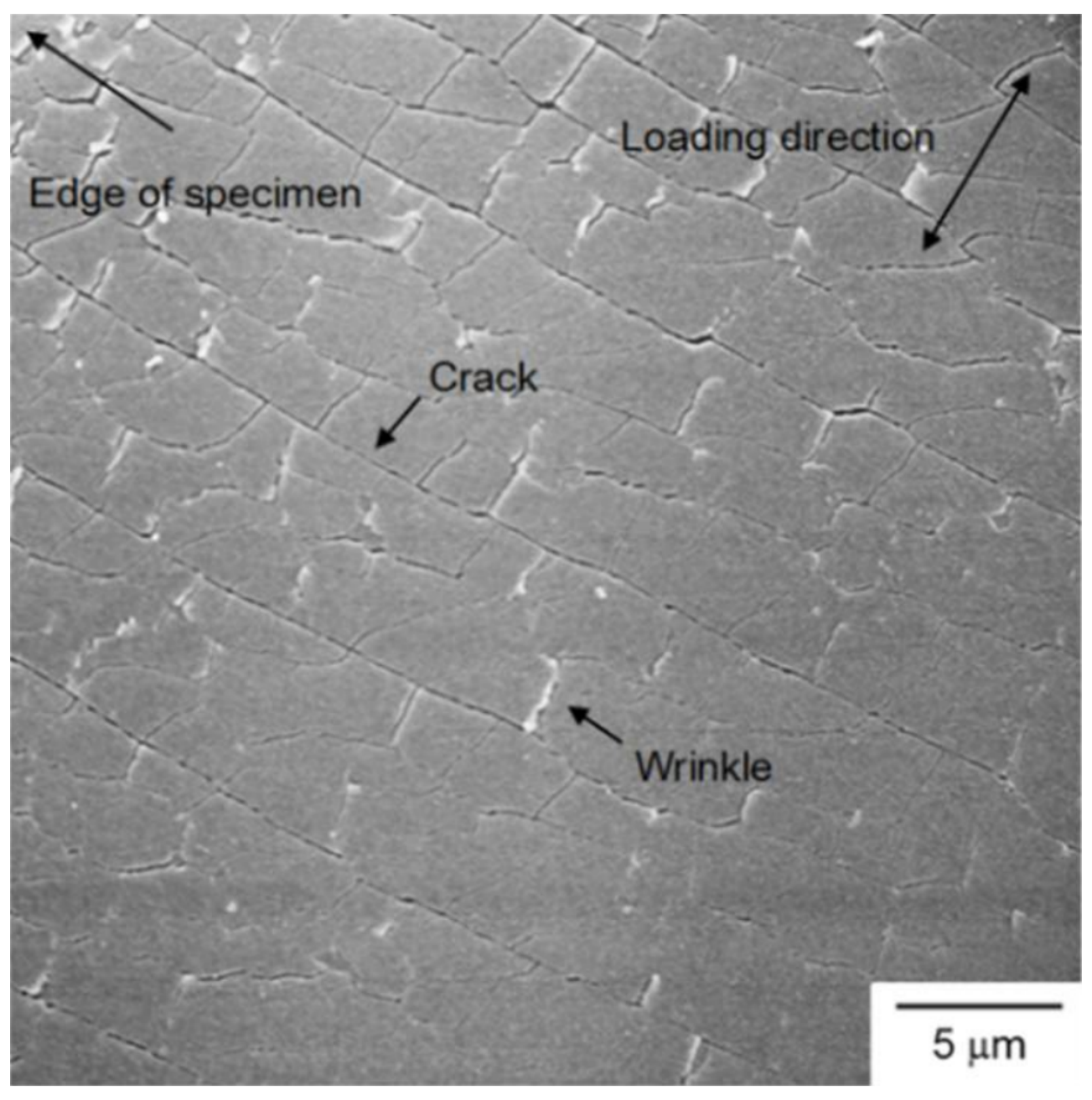
$$\text{Haacke's FoM} = \frac{T^{10}}{R_s}.$$

TC Oxides

Transparent Conducting Oxides are the most common TCMs. They consist in heavily-doped, large bandgap, semiconductors such as indium or fluorine doped tin oxides ($E_{g,\,SnO_2} = 3.7$ eV [3]), which have excellent optical and electrical properties.

However, those TCOs present **two major drawbacks**:

- scarcity of elements (In, F),
- mechanical brittleness.



SEM micrograph of ITO/PET sheet after tensile bending with a 5 mm curvature radius for 1000 h, as viewed from the ITO side, reproduced from [4].

Those drawbacks motivate the search for alternative types of TCMs.

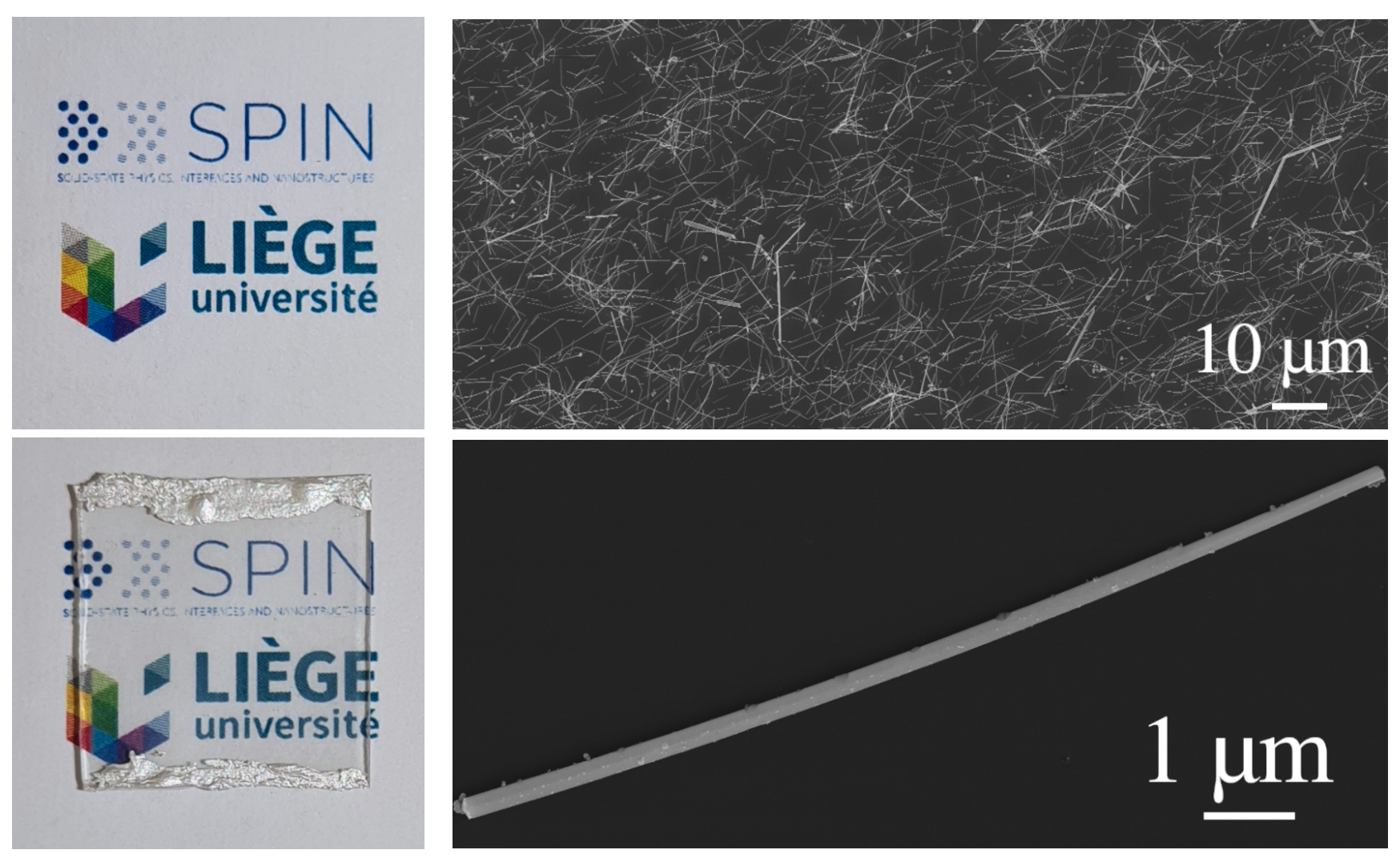
Metallic Nanowire Networks

Metallic nanowire networks form an emergent class of TCMs such that conductive nanowires are randomly deposited on a transparent substrate. If the nanowires are connected in a way that produces at least one path connecting two opposite ends of the substrate, the network is said to have reached **percolation**. This connection allows electrical current to flow while light passes through the gaps. Li and Zhang showed that the density N_c at which a network of widthless nanowires with length l has a 0.5 probability to percolate is given by [5]:

$$N_c l^2 = 5.63726 \pm 0.00002.$$

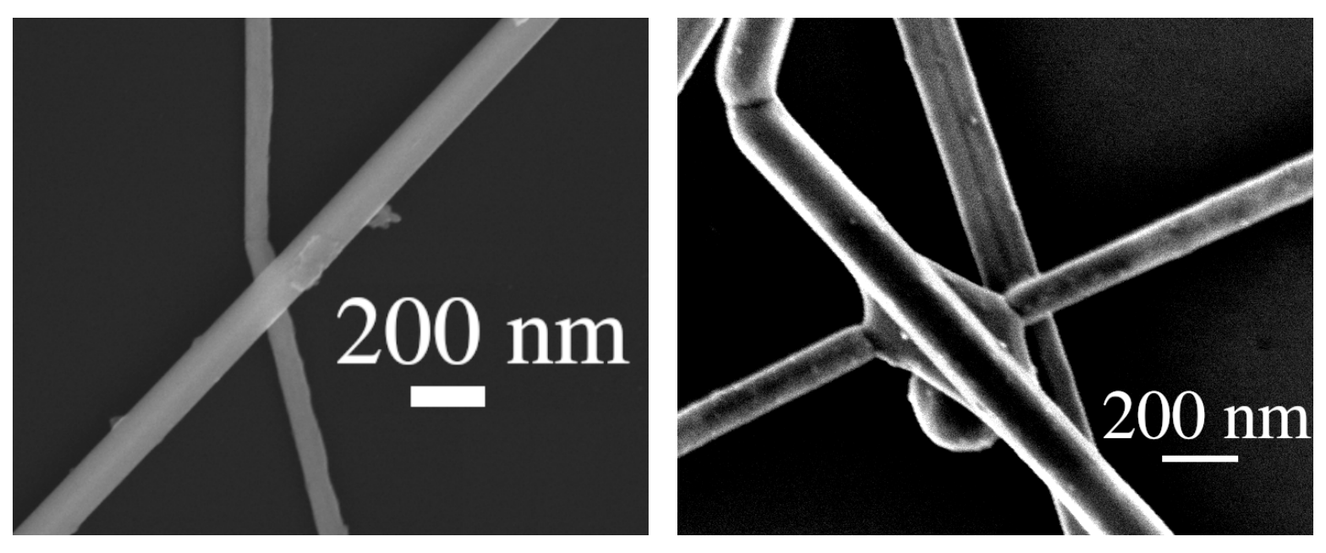
Those networks have several advantages:

- deposition with a low cost solution processing,
- abundance of composing material,
- flexibility.



A typical silver nanowire network, SEM micrographs of:
- a percolated network,
- a single nanowire.

Junction activation - $R_s \searrow$

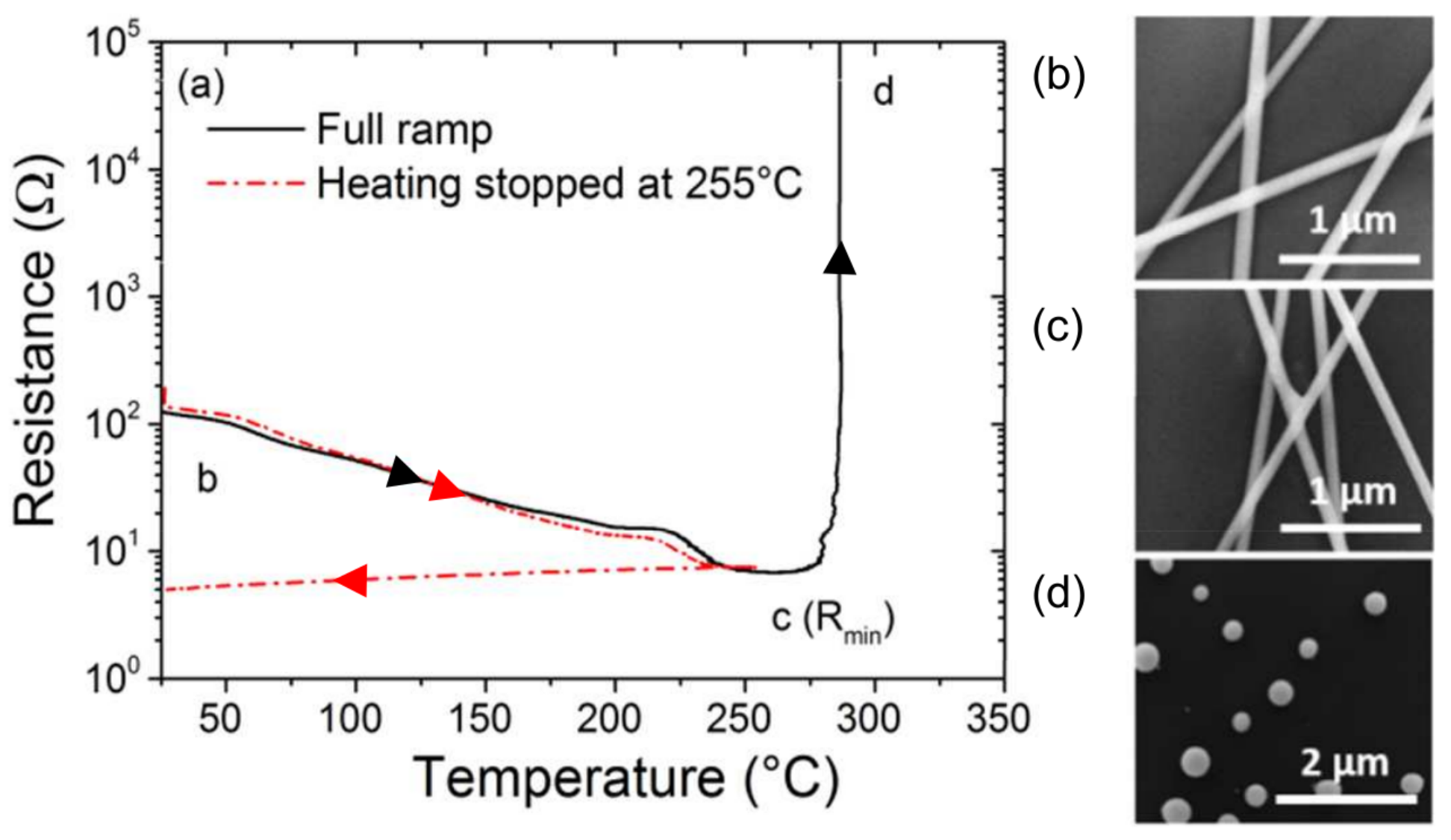


The reduction of the electrical resistance at the nanowire junction, which dominates the R_s value of the network, can be obtained by a range of different techniques:

- thermal annealing,
- Joule effect and electromigration,
- electron beam irradiation,
- low temperature plasma treatment.

Temperature stability

Beyond a temperature in the range of 300° C, nanowires undergo spheroidization due to Plateau-Rayleigh instability, leading to a drastic increasing of R_s.



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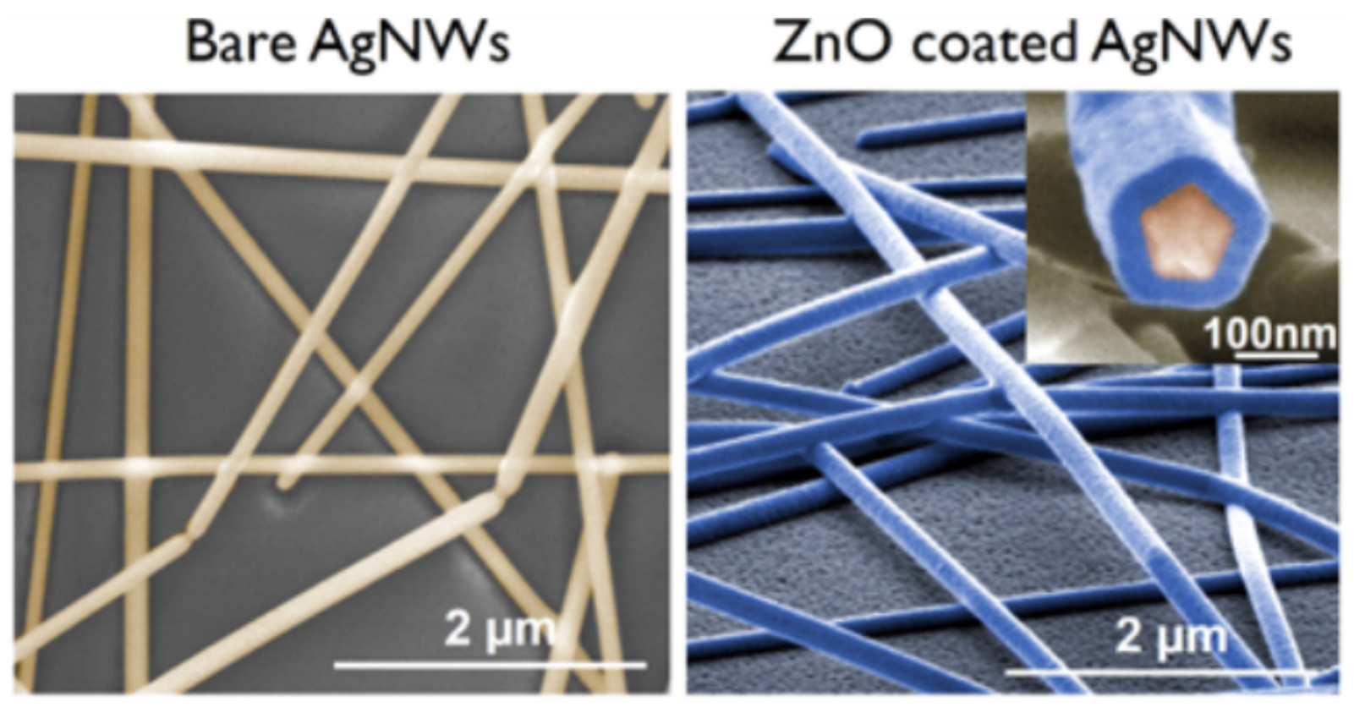
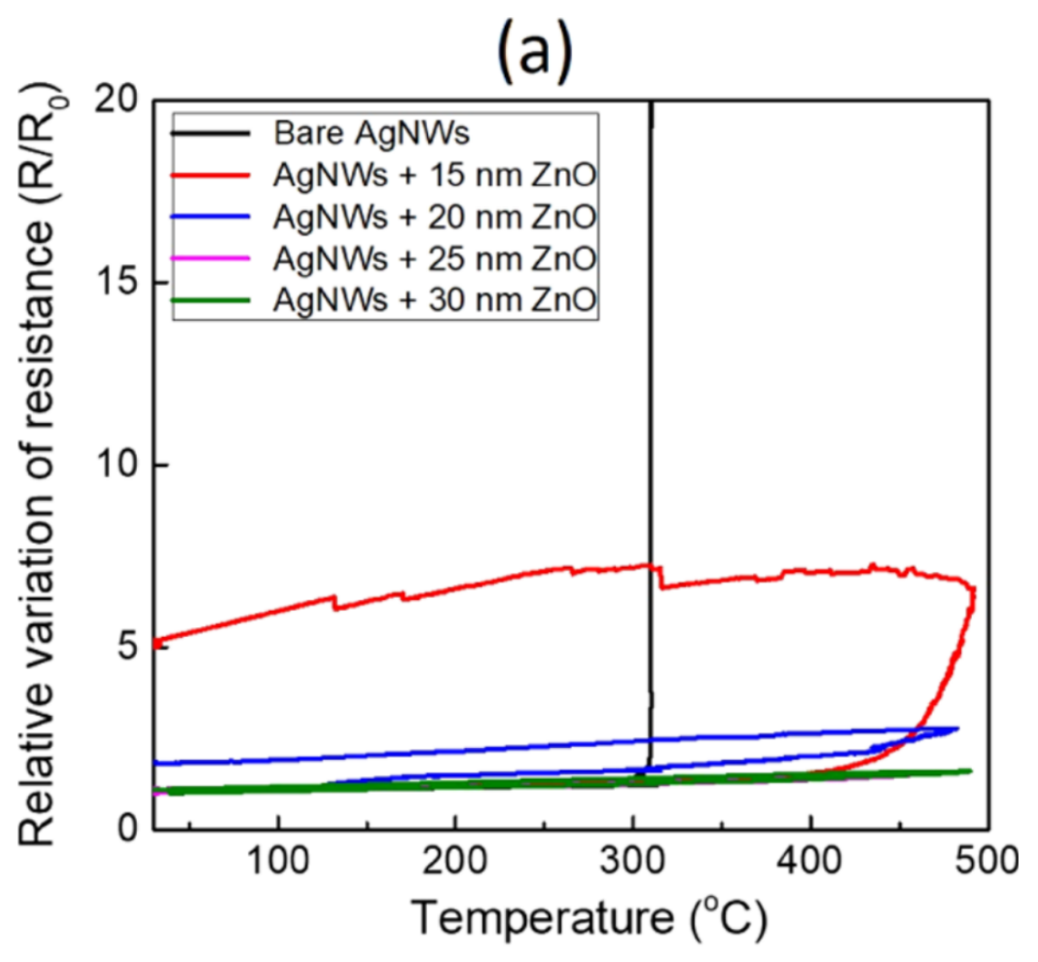
Protective layers can increase the stability of networks [6]:





References

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