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Coated Glass for Energy Efficient Buildings: Spectral Selectivity, Angular Dependence & Time Variability

C. G. Granqvist
Uppsala Universitet

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Coated Glass for Energy Efficient Buildings:

Spectral Selectivity, Angular Dependence & Time Variability

C.G. Granqvist

The Ångström Laboratory, Uppsala University, Sweden
ChromoGenics AB, Uppsala, Sweden

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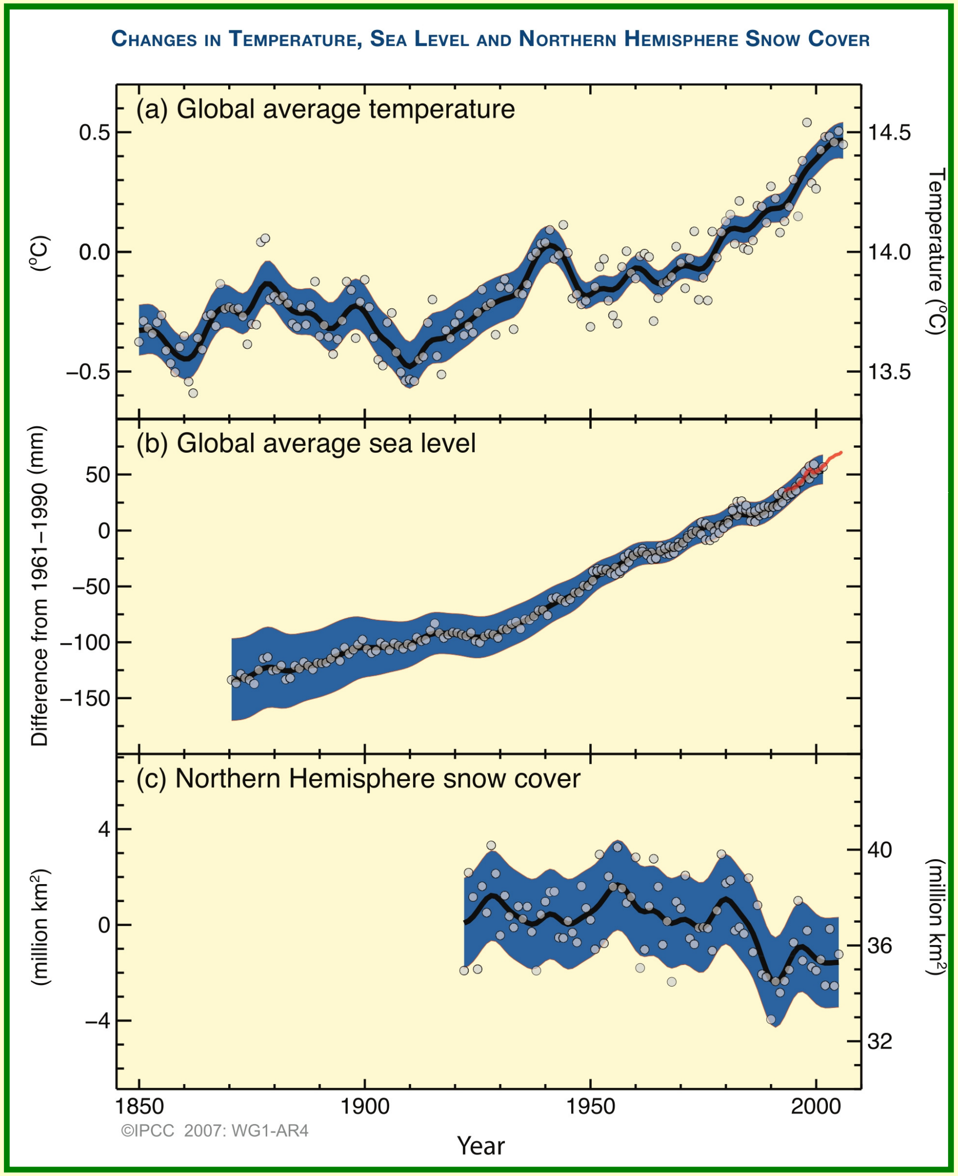
Environmental challenges



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Ice coverage in the Arctic

- **Lowest ice coverage in recorded history (2012)**
- **And it is NOW!**

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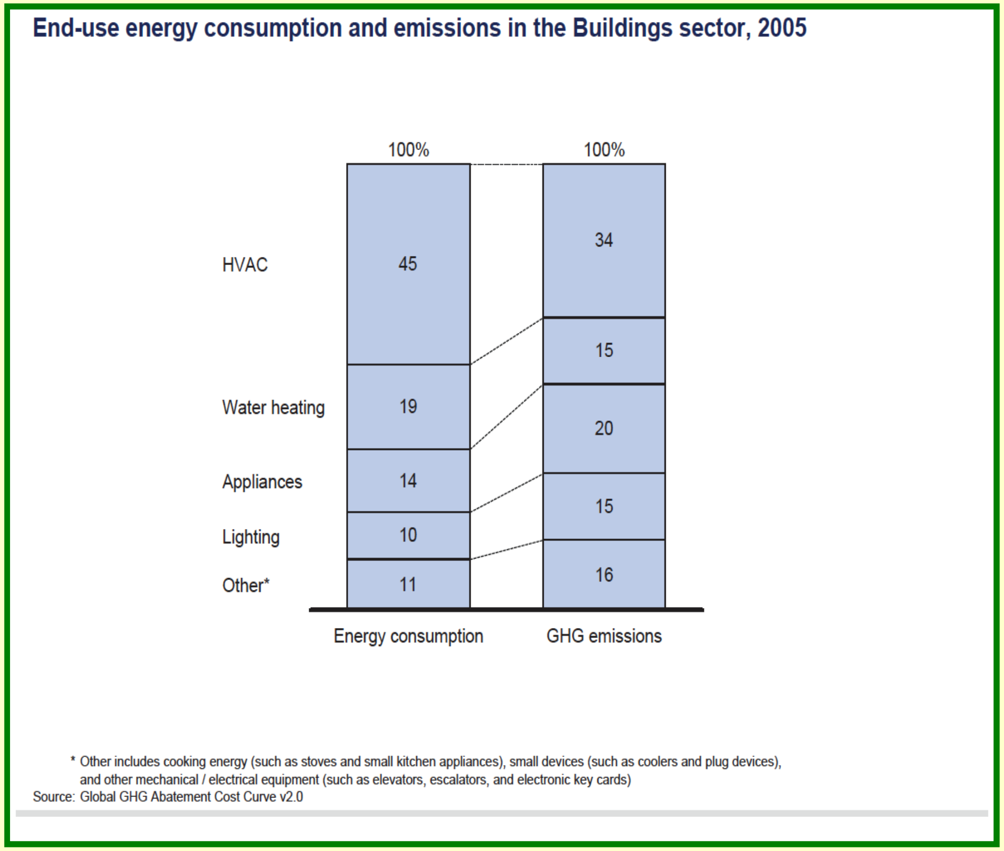
Why bother with buildings & windows

- Global warming
- Increasing sea level
- Increasing CO_2
- Increasing population
- Energy savings are needed
- Buildings use ~40% of all energy
- We spend 80 – 90 % of our time indoors
- Windows are ”weak links” in buildings



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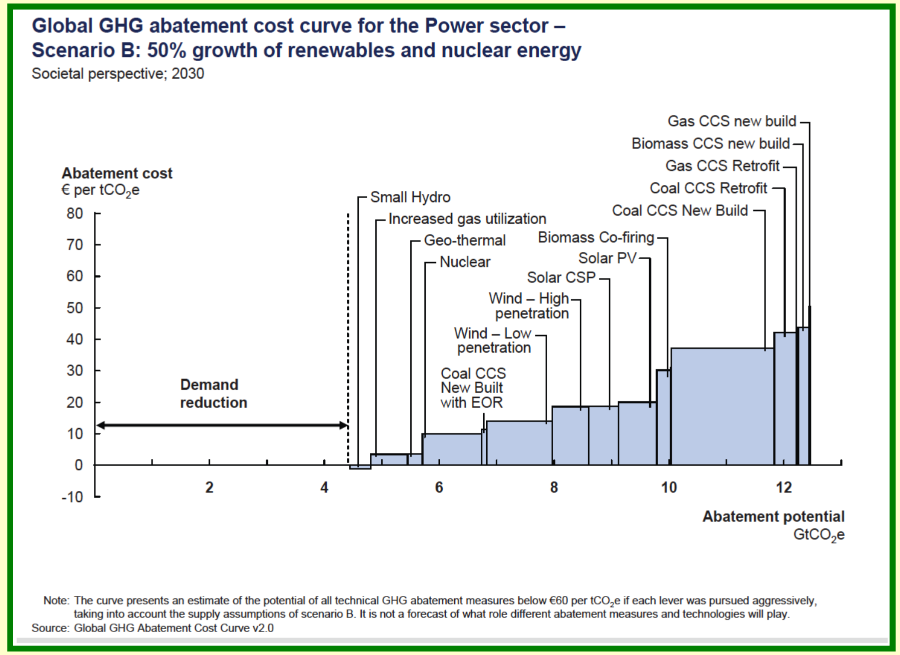
It is cheap to improve buildings!

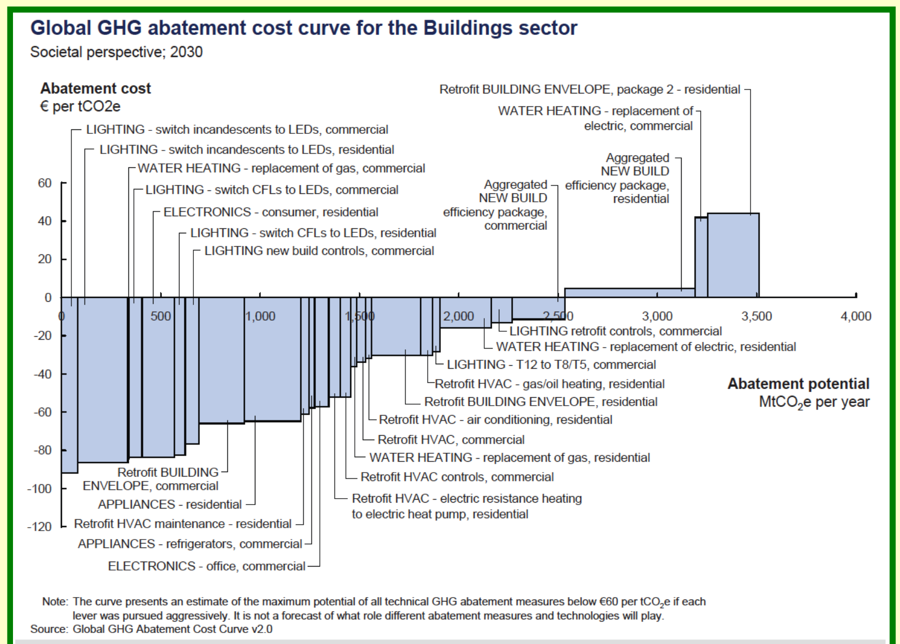
Greenhouse gas abatement costs:

For power generation



For buildings

(negative cost!!)



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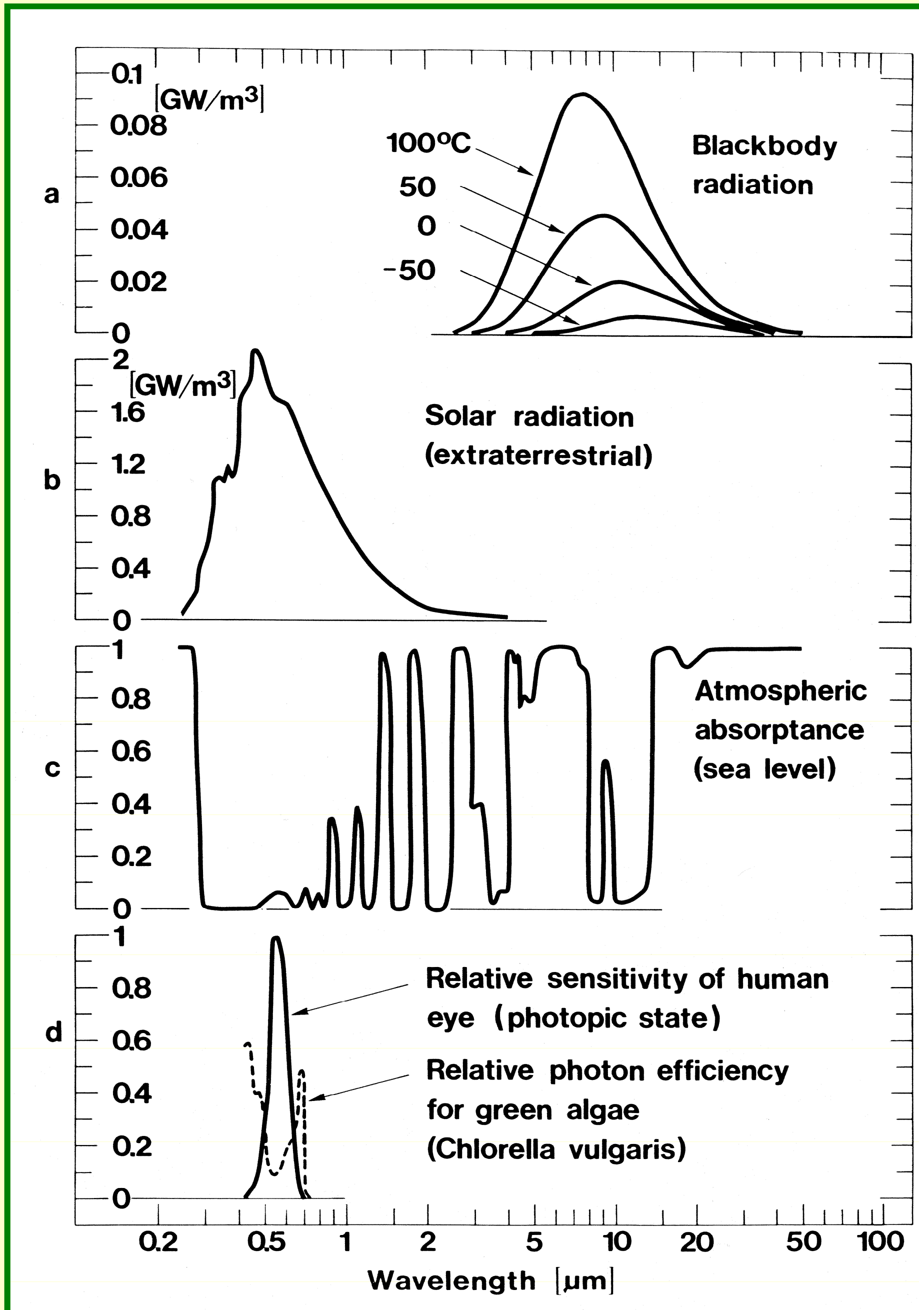
Ambient radiative properties

Key features:

- Spectrally selective
- Angular dependent
- Time-variable



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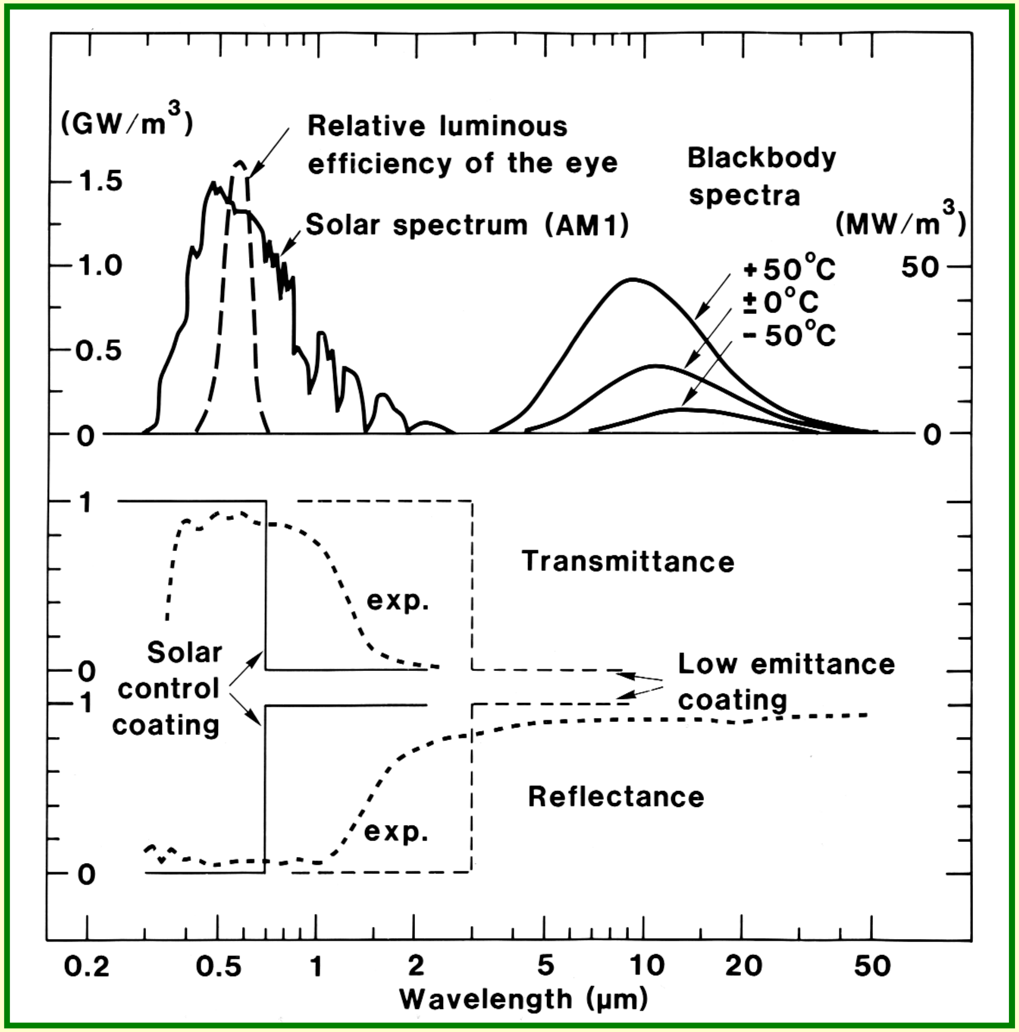
Window coatings: Spectral selectivity & electrical conduction

Two principle types:

- Solar control
- Low emittance



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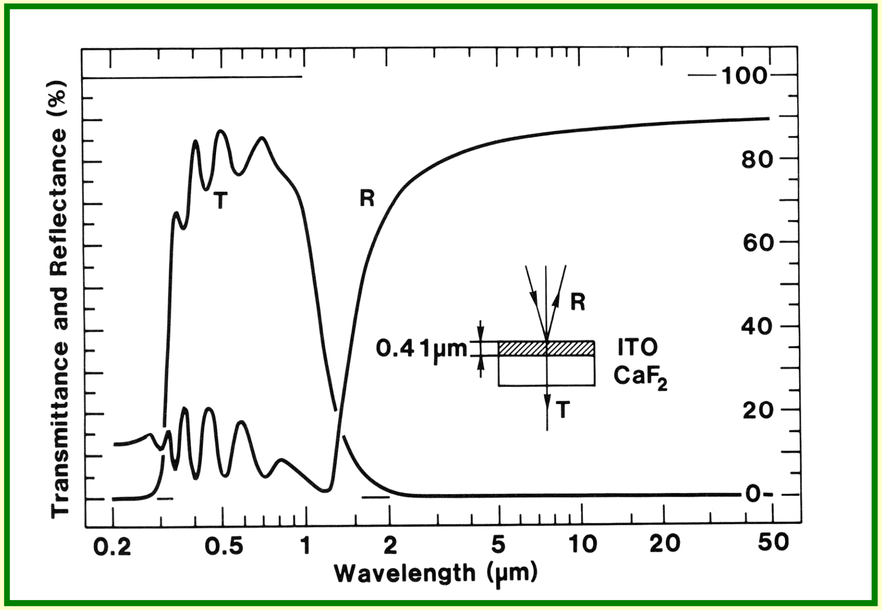
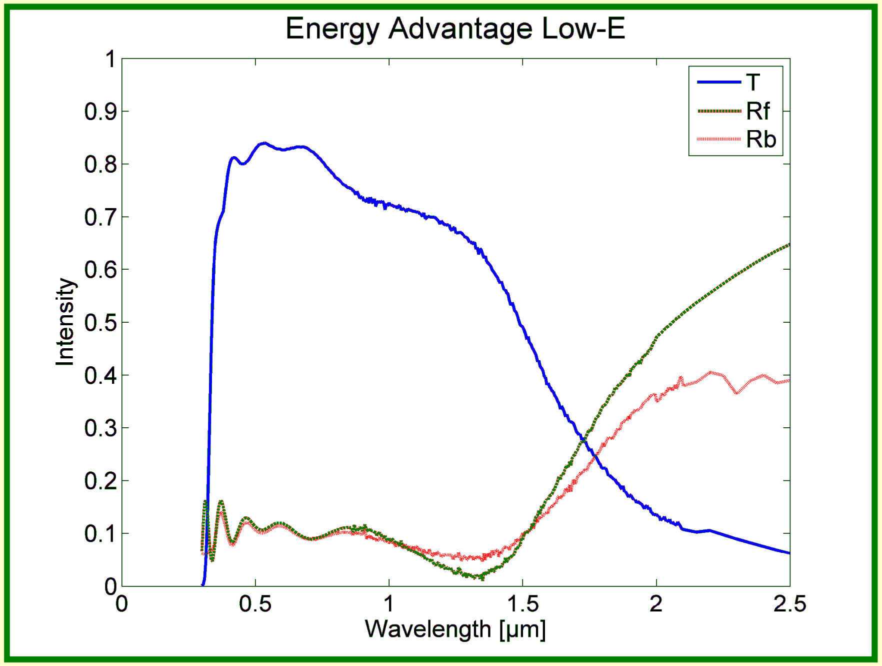
Wide band gap heavily doped semiconductors

- SnO_2:F (FTO), In_2O_3:Sn (ITO), ZnO:Al (AZO), ZnO:Ga (GZO), TiO_2:Nb…
- High transmittance
- Infrared reflectance
- Resistivity ~10^{-4} Ωcm
- Thickness ~200 nm
- Theoretically understood





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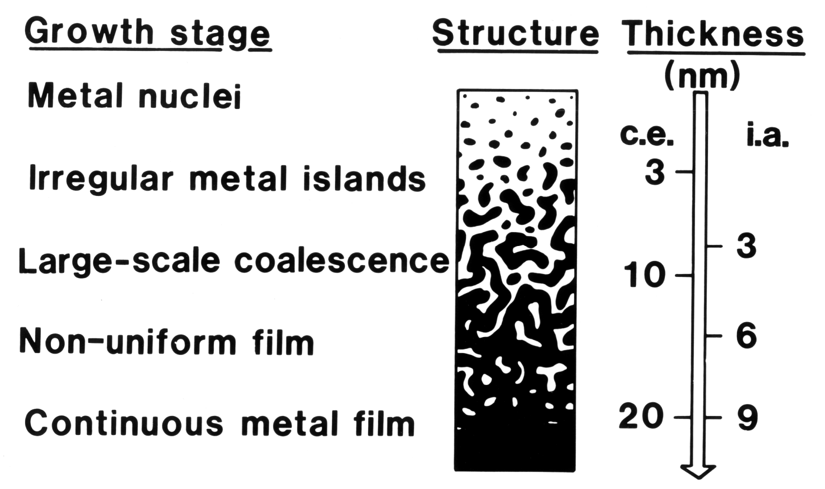
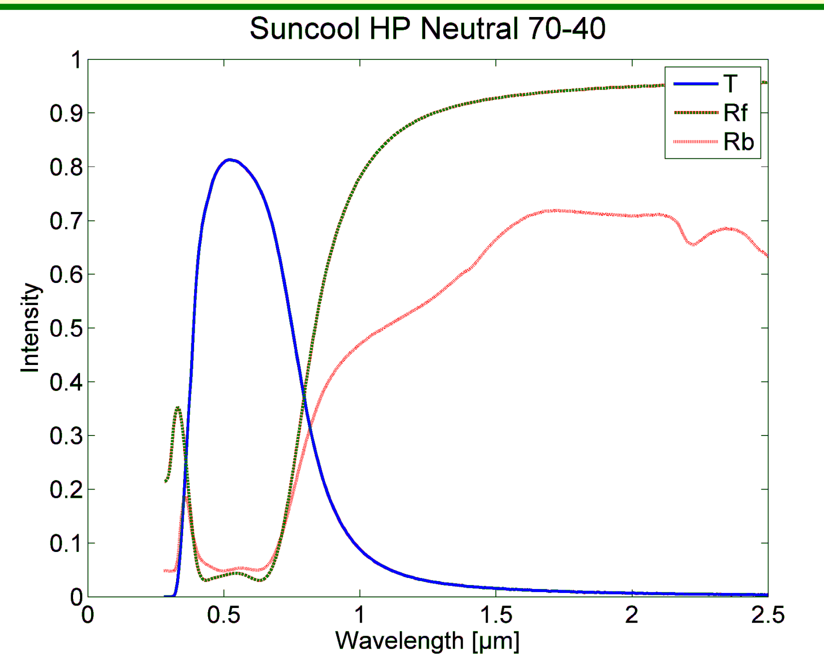
Metals

- Examples:
  ZnO/Ag/ZnO
  $TiO_2/Au/TiO_2$
  ZnO/Ag/ZnO/Ag/ZnO
  acrylic/Ag-Au/acrylic…
- Metal thickness ~10 nm
- Dielectric thickness ~100nm
- Reflecting in NIR





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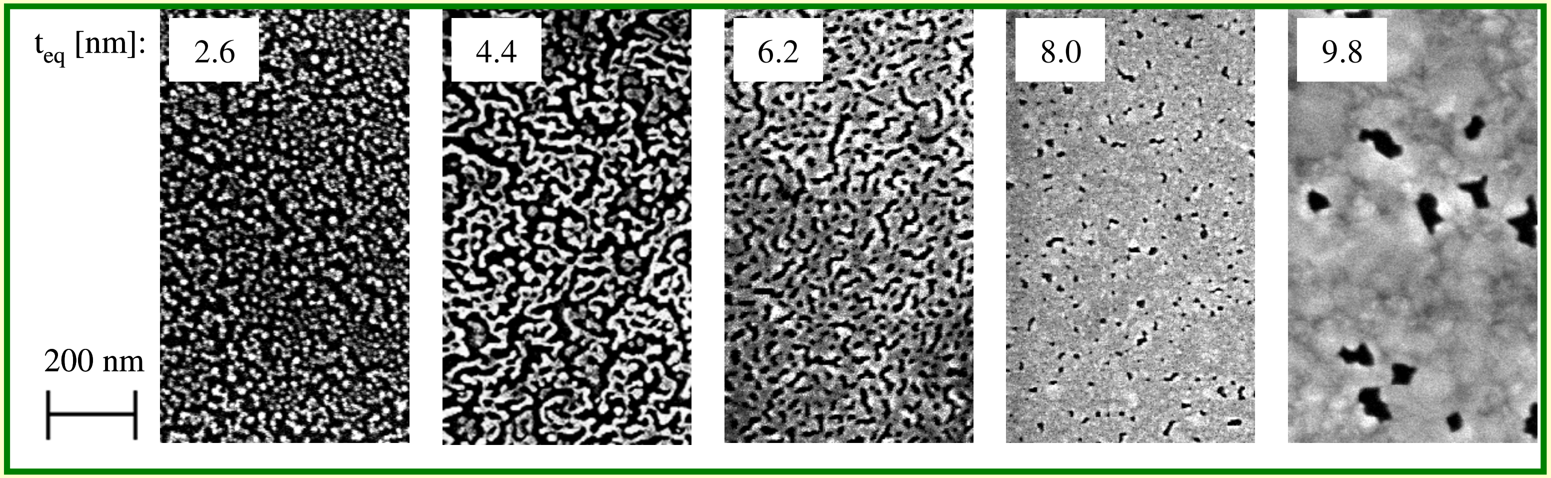
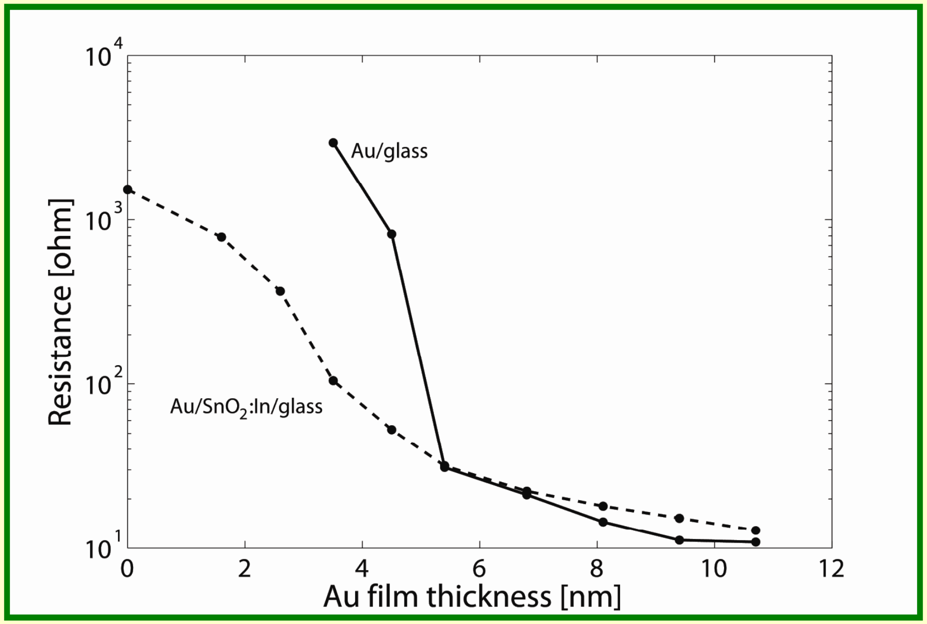
Thin metal films: The role of the substrate



Resistivity of Au on glass and SnO_2:In



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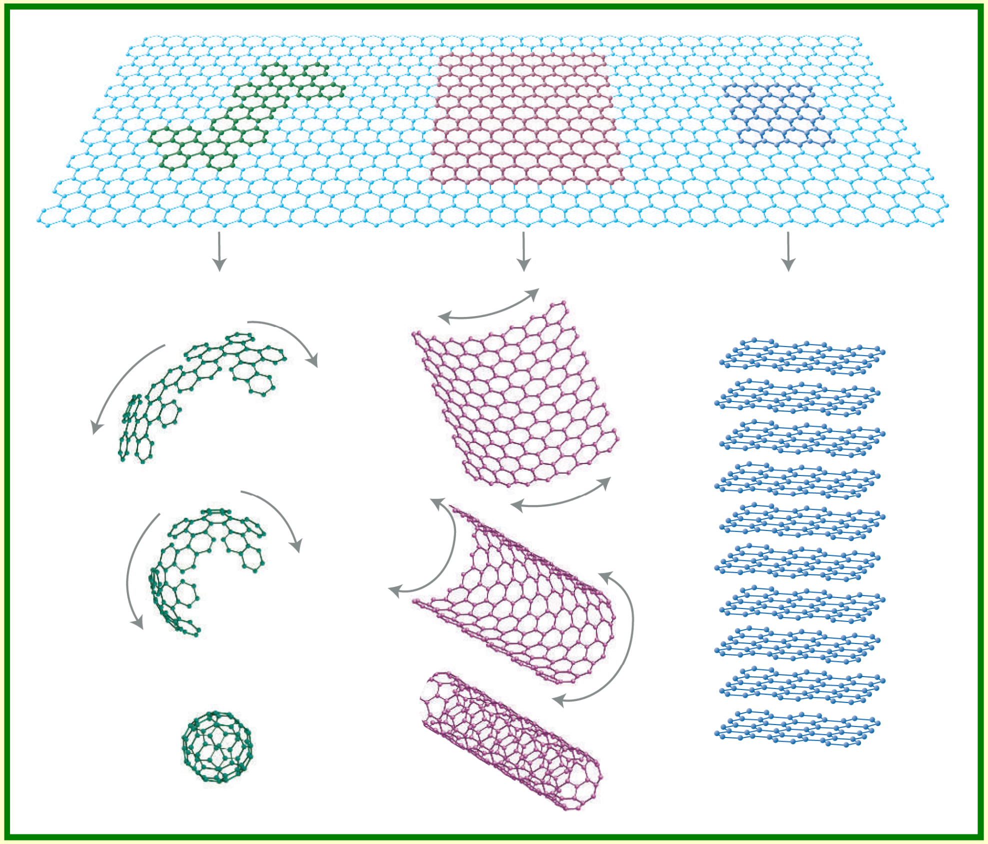
Transparent conductors: New carbons

- Graphene monolayer
- C_{60} ”buckyball”
- Nanotubes



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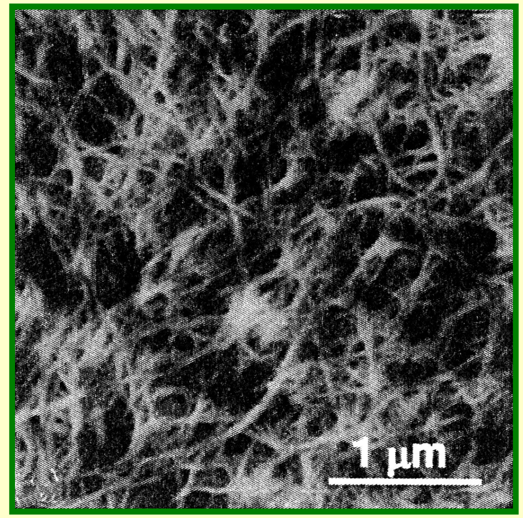
Transparent conductors: Meshes

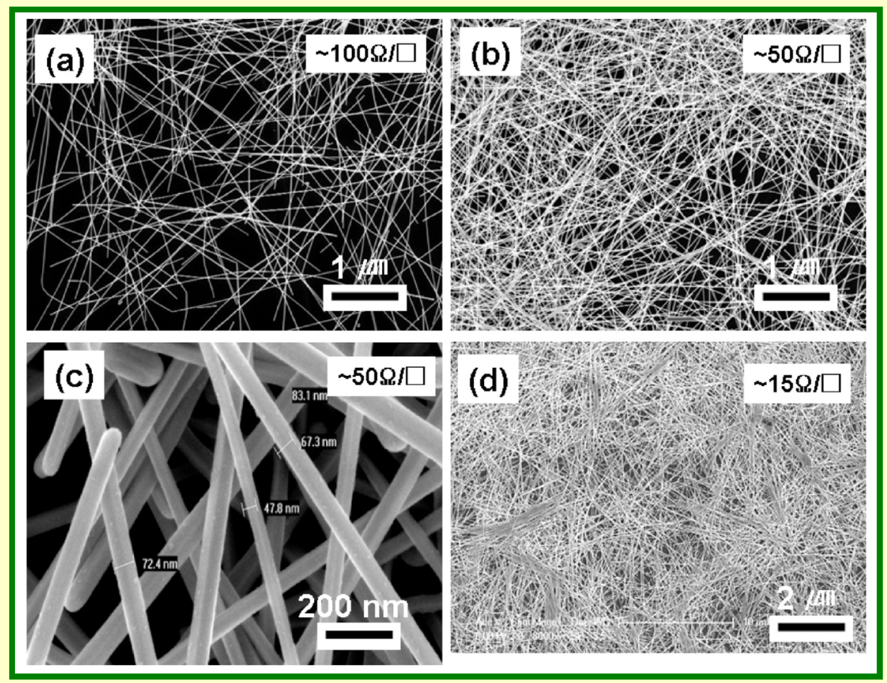
Carbon nanotubes:

- No haze
- Transparent in NIR
- Cannot (yet) (quite) match ITO



Silver:

- Cheap
- Some haze



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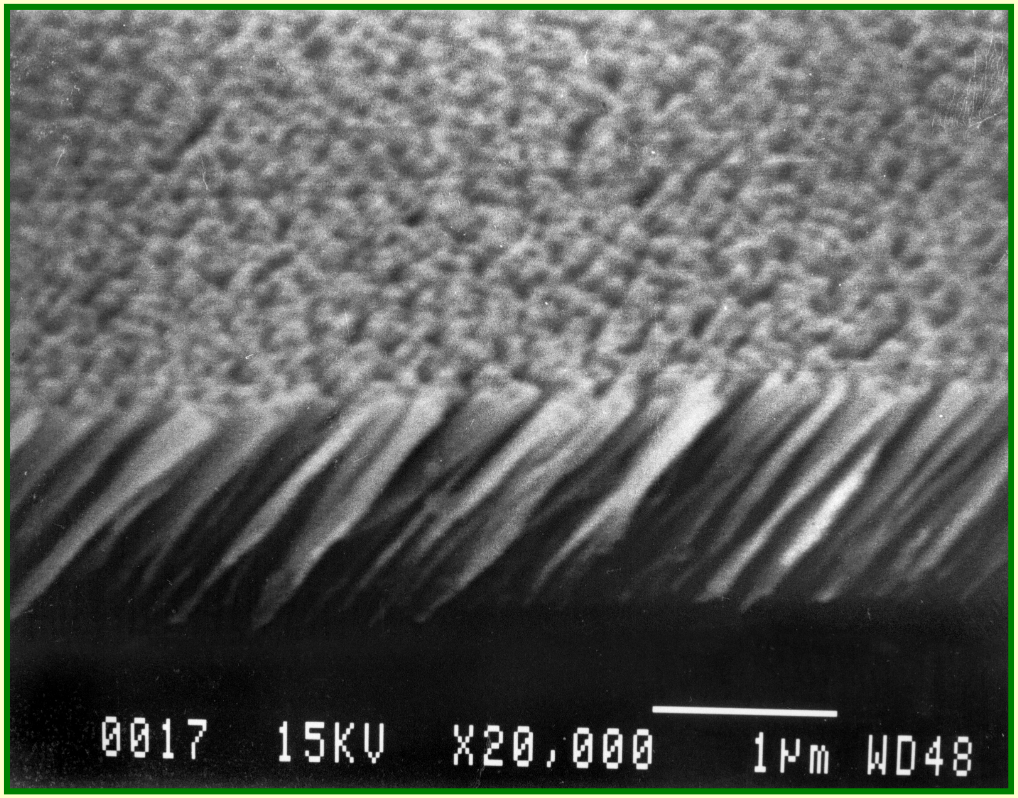
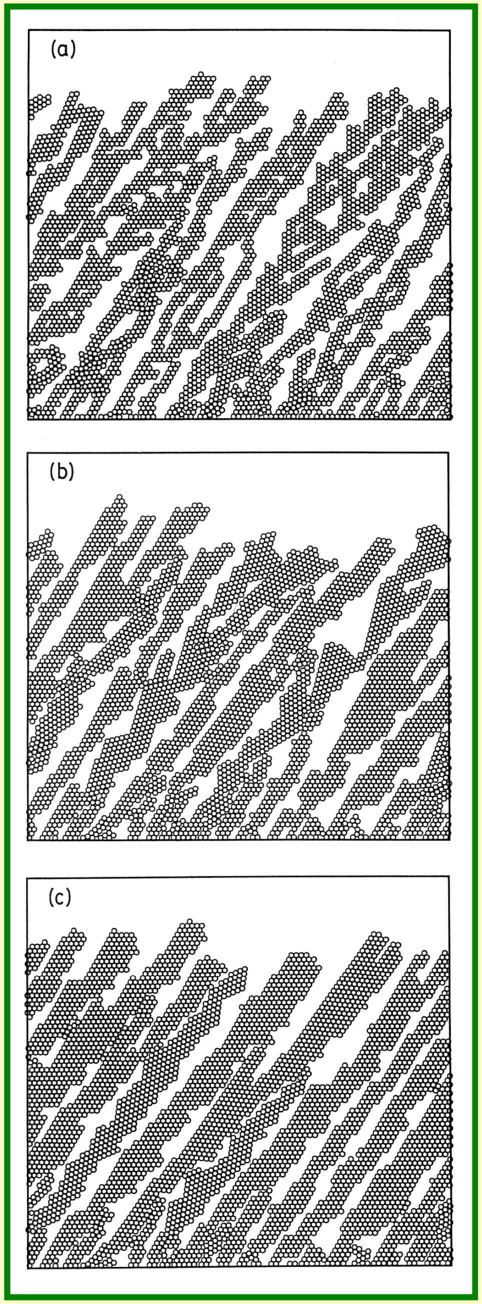
Angular selective thin films

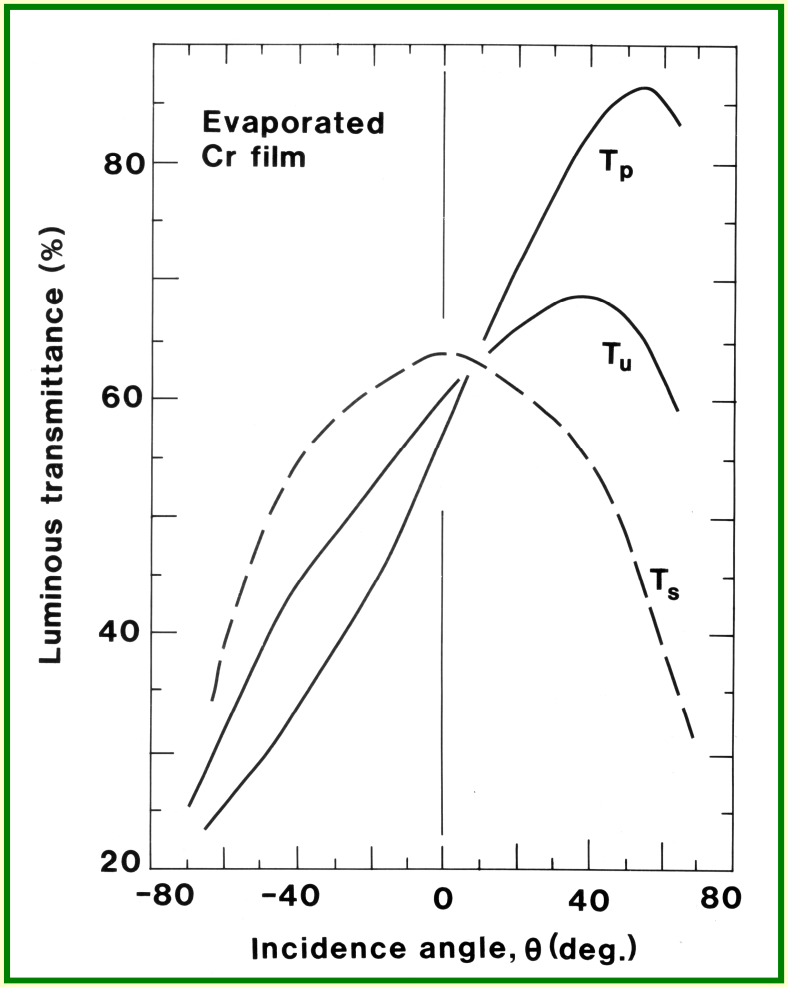
Modelling →

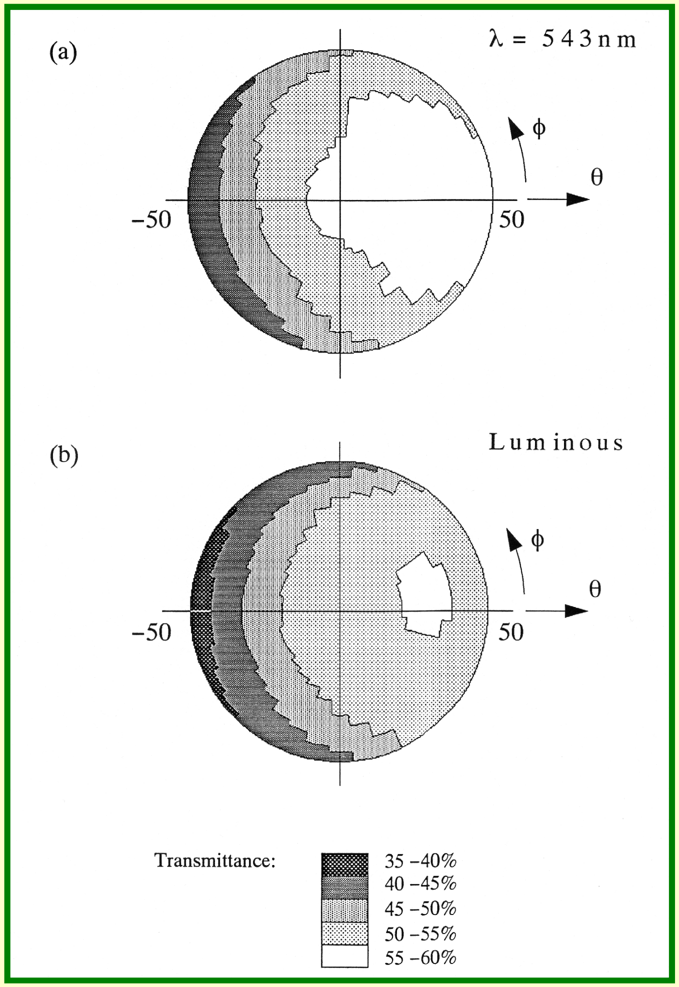
SEM of Cr-based film ↓





Angular selective transmittance





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Time variability: The chromogenic technologies

Photochromic (UV light)

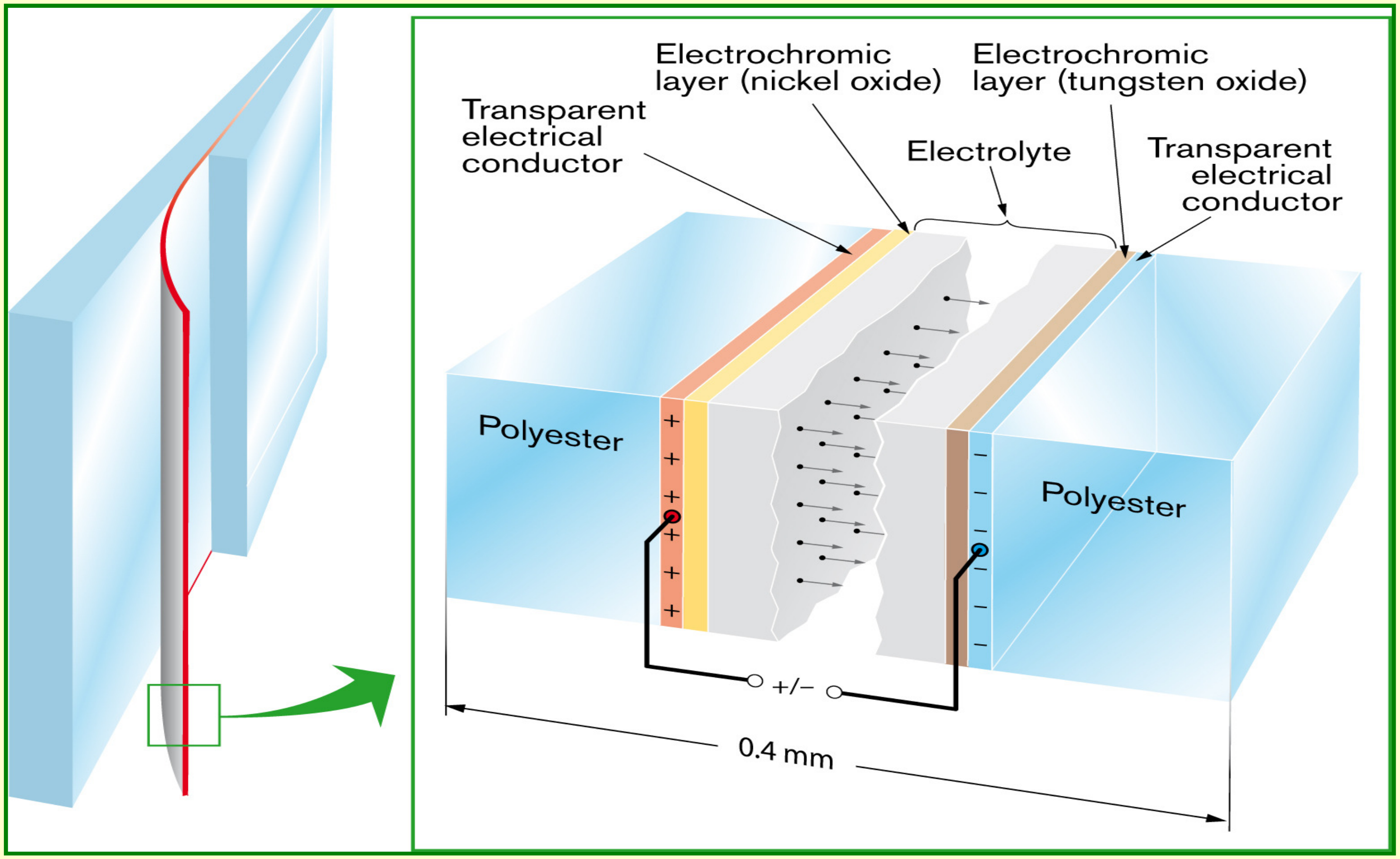
Thermochromic (temperature)

Electrochromic (electric charge)

Gasochromic (reducing/oxidizing gas)

Electrochromic (EC) device design

Thin-film battery with visible charge



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Electrochromics:
Specific device designs

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Monolitic:

- **All-thin-film**
- **Glass substrate**

- ***Sage/S.t Gobain***
- ***Soladigm***

Laminated:

- **Films/laminate/films**
- **Glass on PET substrate**

- ***E-control (glass)***
- ***GESIMAT (glass)***
- ***ChromoGenics (PET)***

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Some implications of the battery model

- Open circuit memory of transmittance
- Intermediate transmittance levels
- Non-instantaneous transmittance changes
- Physical processes at the atomic scale, i.e., no haze
- Color matching by two EC films
- Polymer electrolyte can give added functionality (spall shielding, burglar protection, acoustic damping, thermo-chromism…)

Six challenges for EC devices

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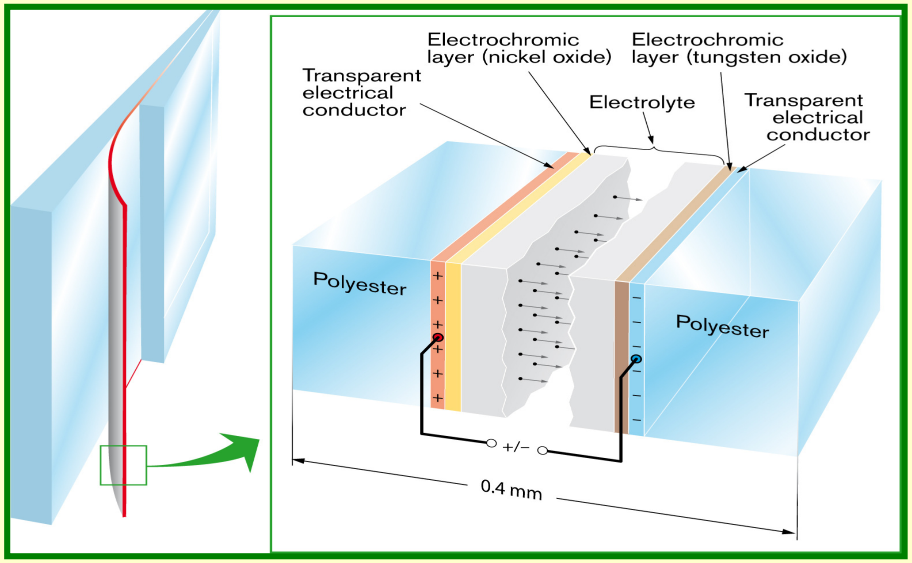
- *EC films: Nanocrystalline & nanoporous*
- *Transparent conductor: ~20 Ω, T ≈ 90%*
- **Efficient charge insertion/balancing**
- *Elecrolyte: good ion conductivity, UV stability, (adhesion)*
- **Long-term durability: Good strategy for voltage & current control**
- *Large-scale manufacturability*



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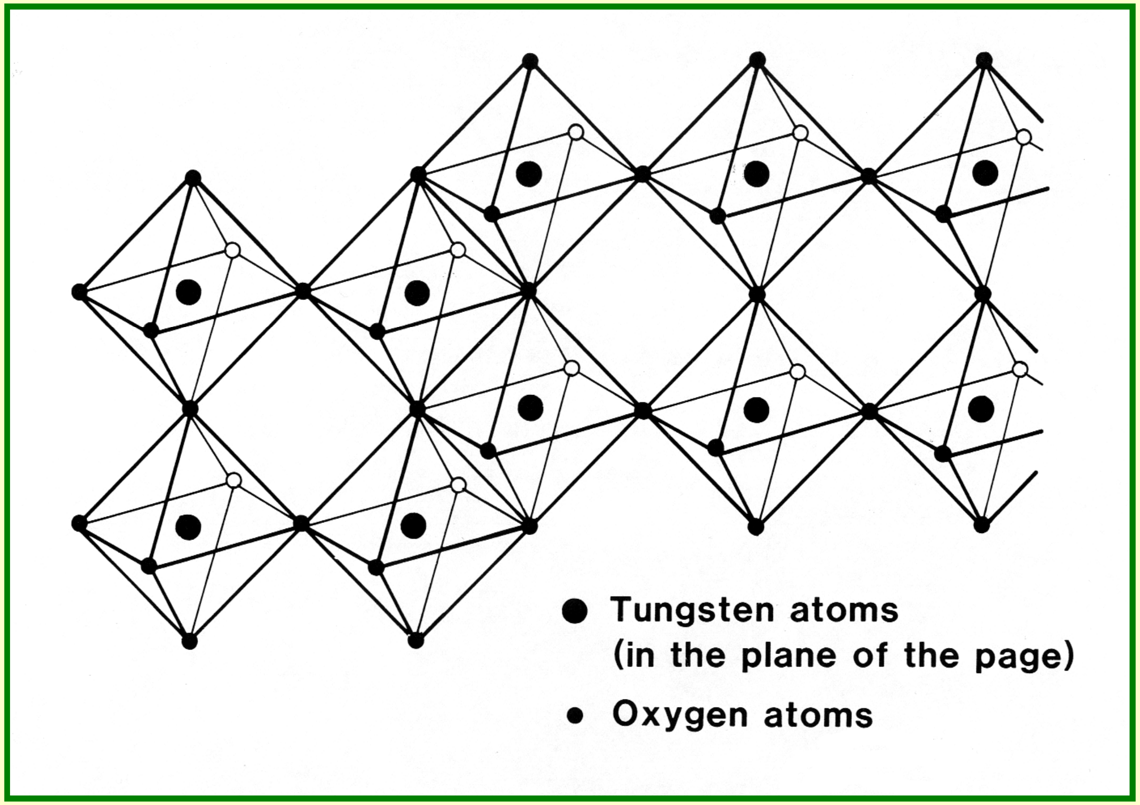
EC oxides: Unifying feature

The ubiquitous octahedron

Implications:

- **Electronic structure**
- **Ion diffusion**



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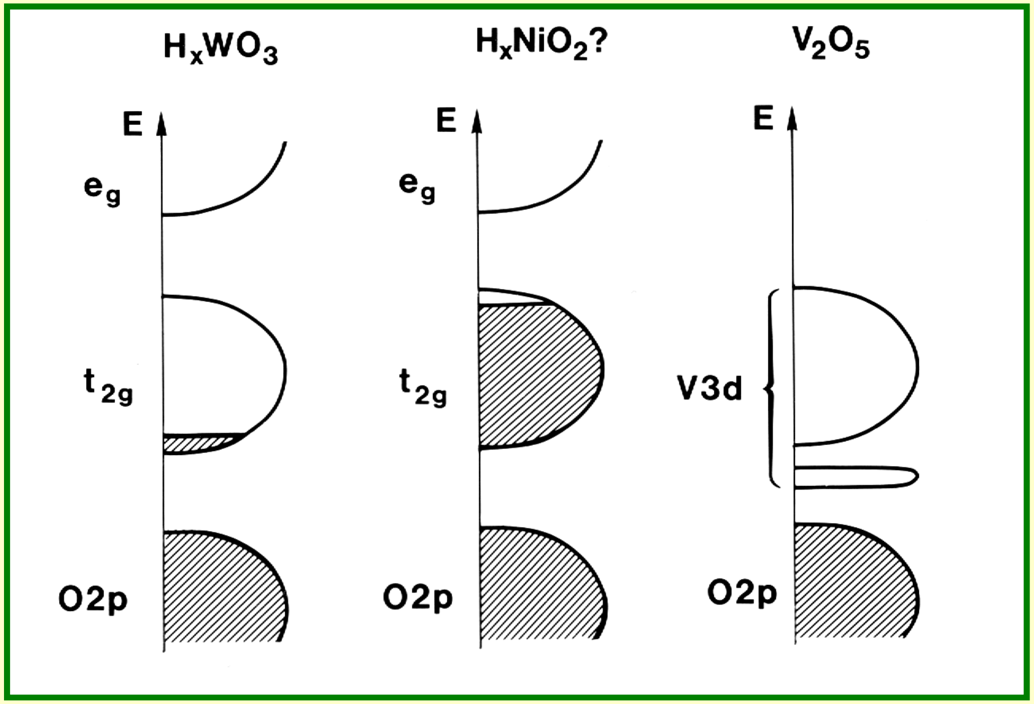
EC oxides: Absorption by polarons etc

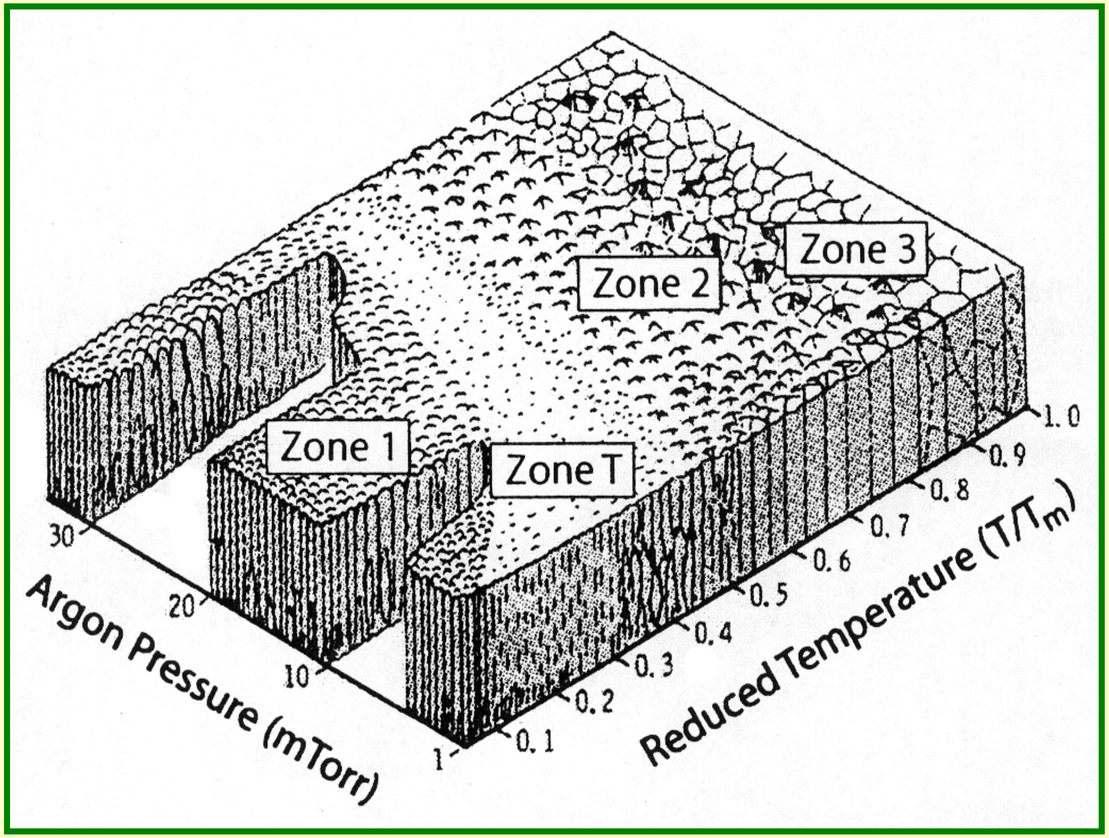


Photon-induced electron transfer between neighboring metal ions (*i* and *j*):

$$W_i^{5+} + W_j^{6+} + \text{photon} \rightarrow W_i^{6+} + W_j^{5+}$$

Nanoporosity in sputter deposited films

- Large pressure
- Low temperature



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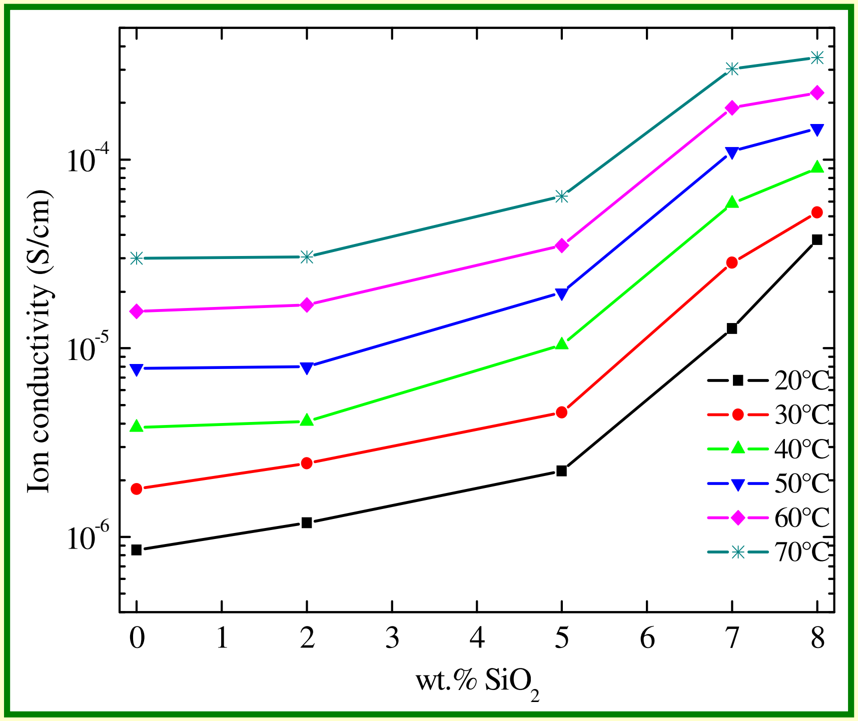
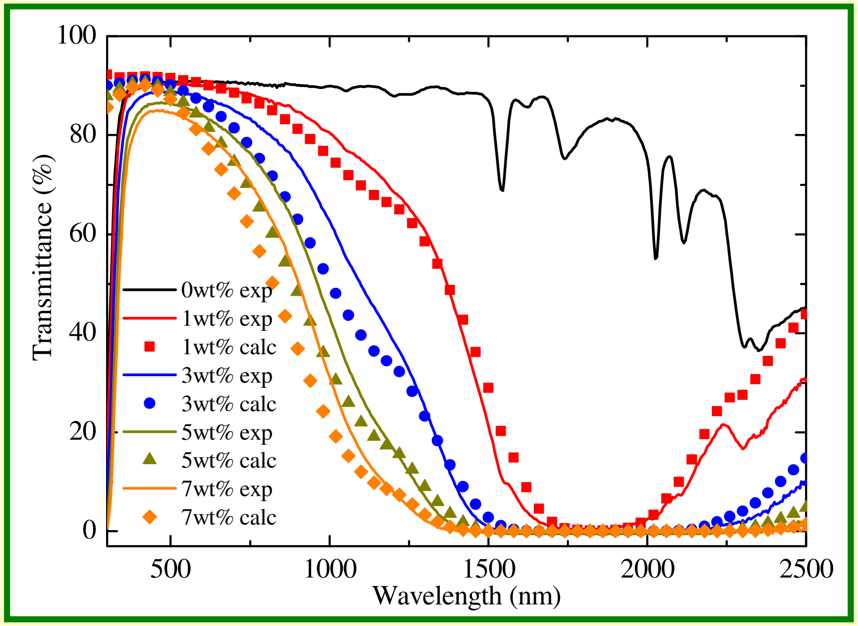
Polymer development

PEI-LiTFSI with nanoparticles

- **Increased ion conductivity with SiO_2 →**
- **Near infrared absorption with ITO →**





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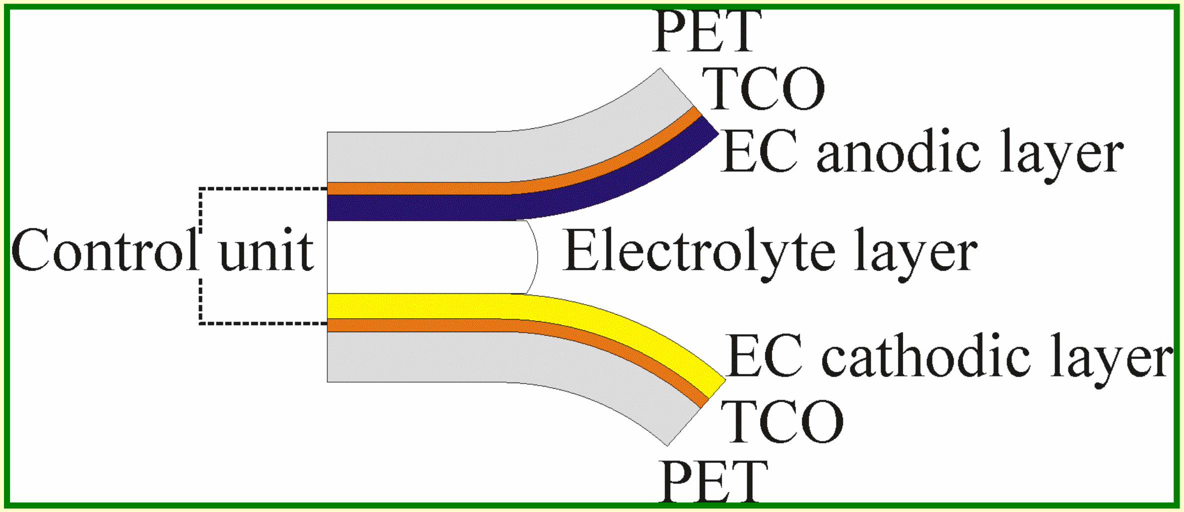
Electrochromic foil: General design



Electrochromic foil: State-of-the-art

PET/ITO

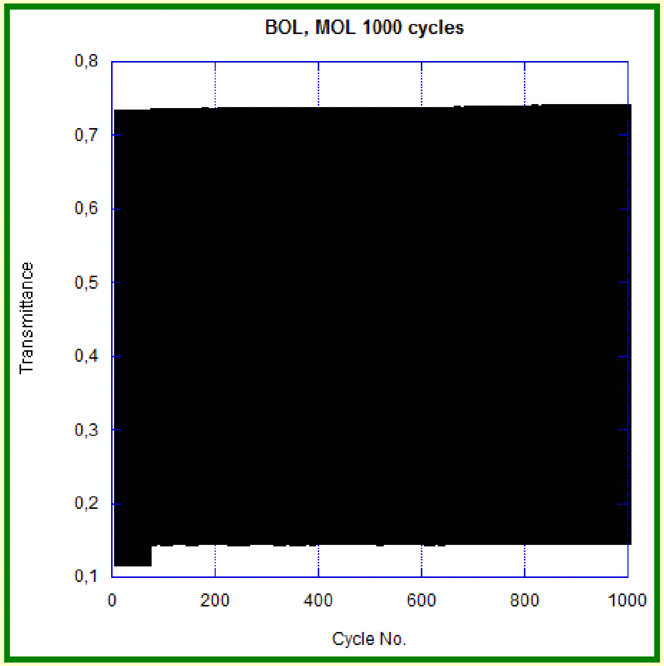
WO_3

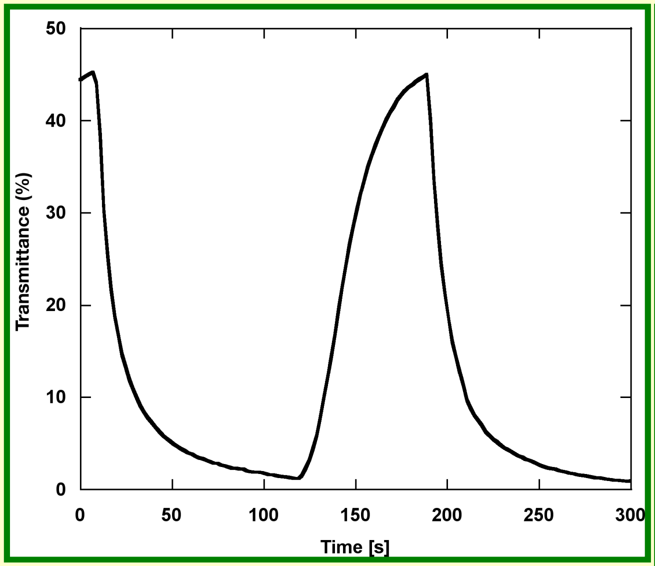
”rubber” electrolyte

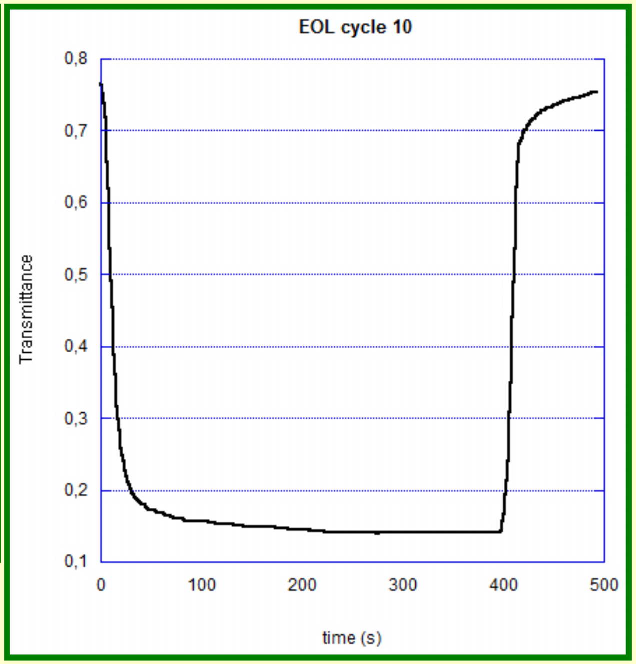
”NiO”

ITO/PET

5 x 5 cm^2







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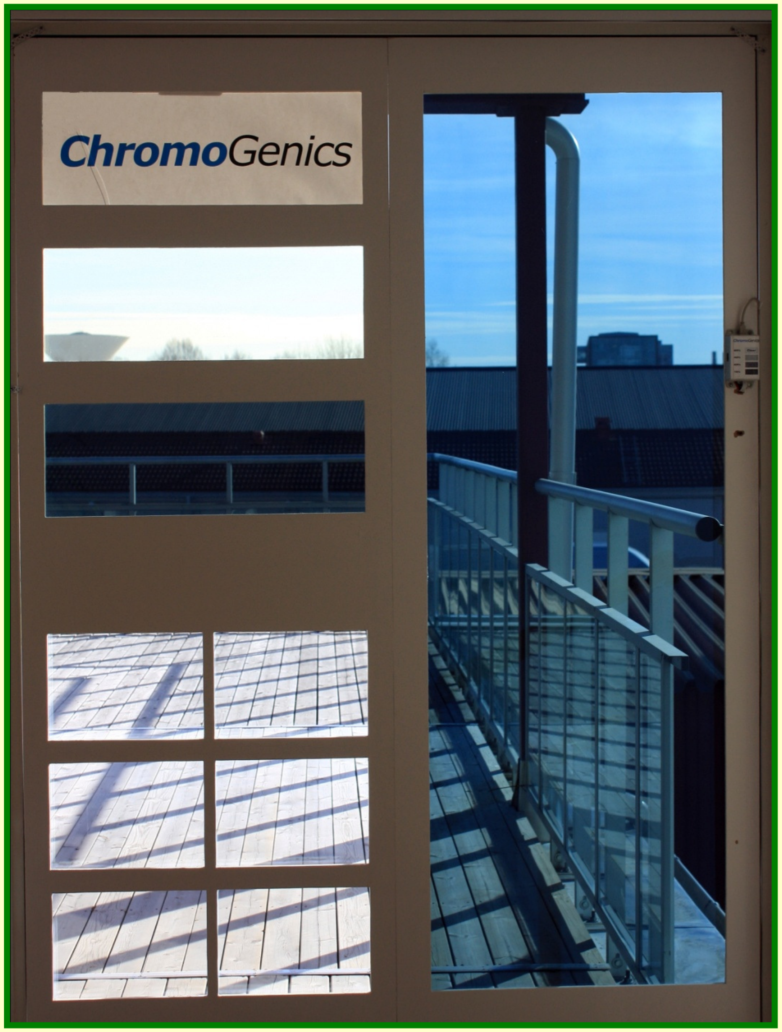
Foil-based smart window prototype: 0.8 x 1.8 m²



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Smart window, ~25 m^2

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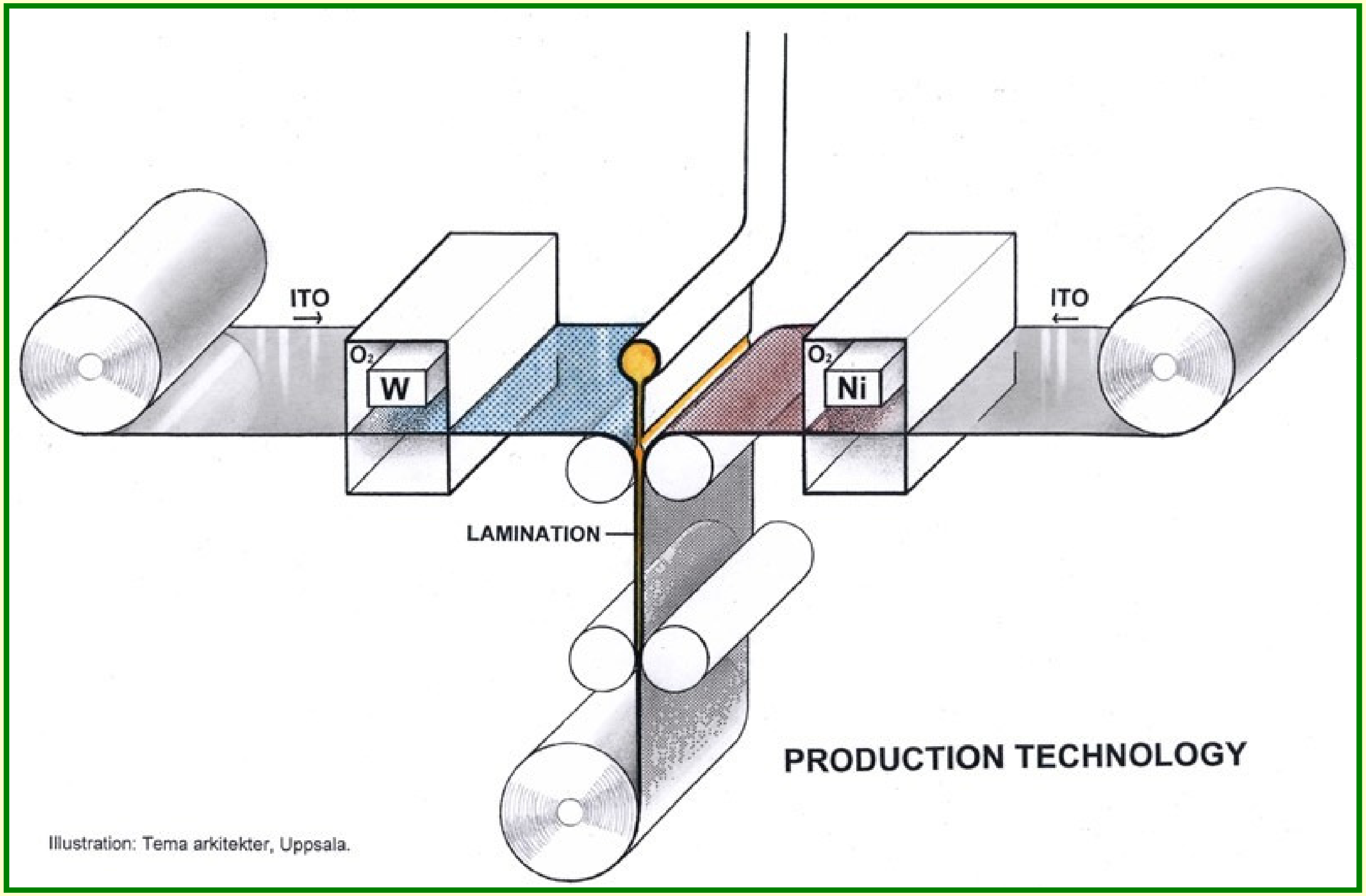
Electrochromic foil: R2R manufacturing



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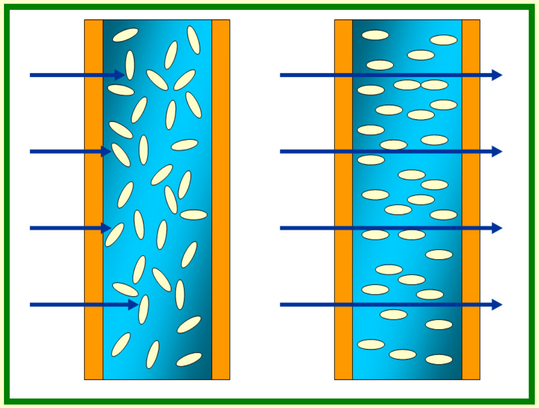
Alternative EC device types

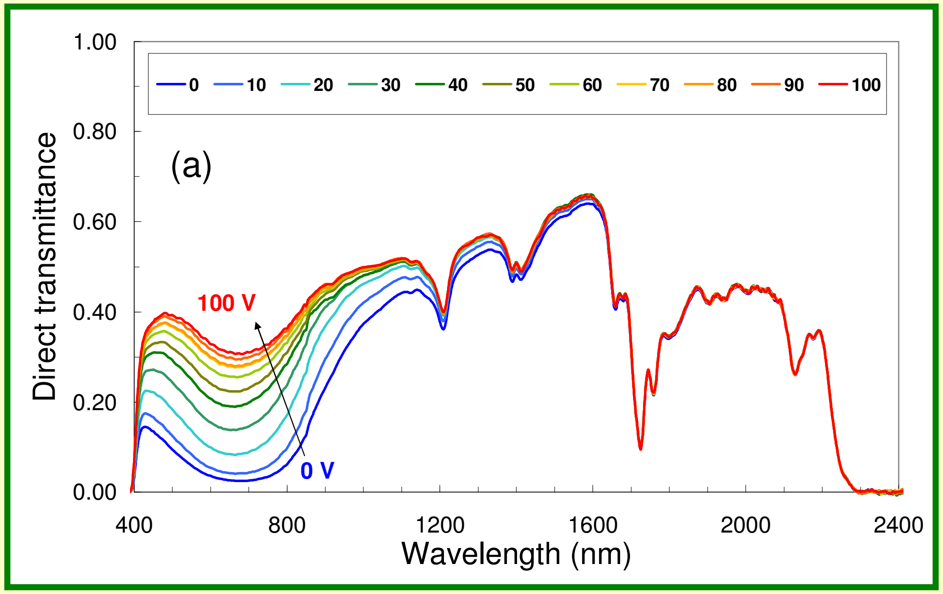
- **Metal hydrides**
- **Polymer dispersed liquid crystals**
- **Suspended particle devices**
- **Reversible electroplating**
- **Variable plasmon absorption in transparent conducting nanoparticles**

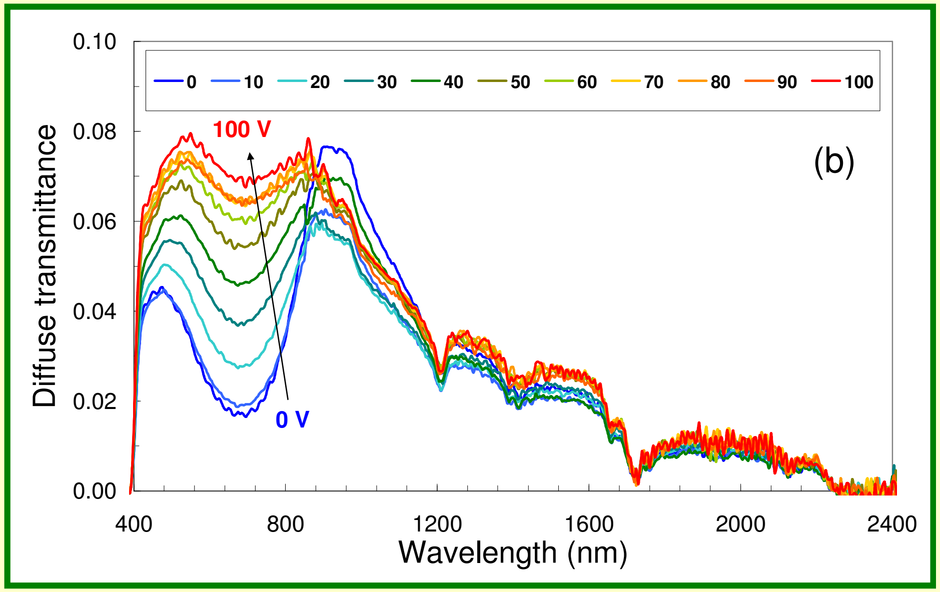
…..

Suspended particle devices

- Modulation of visible light only
- Some scattering

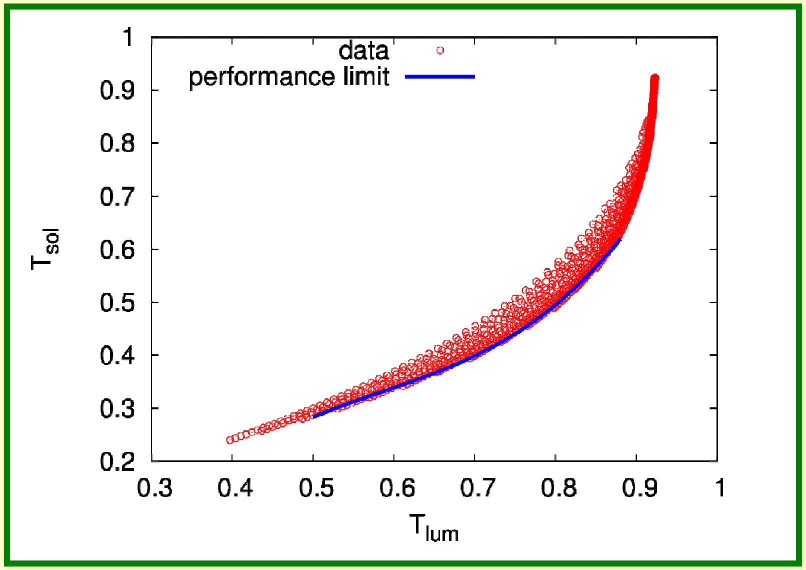


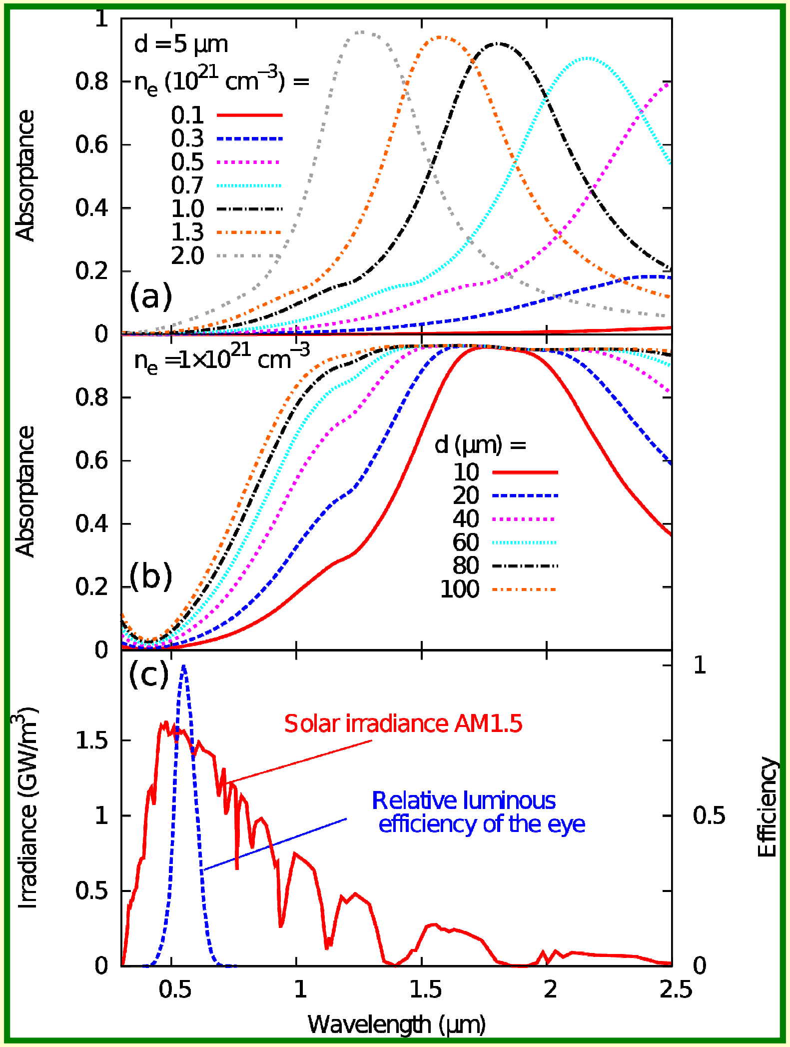




Variable plasmon absorption

- **Calculated data**
- **1 vol% ITO in "glass"**





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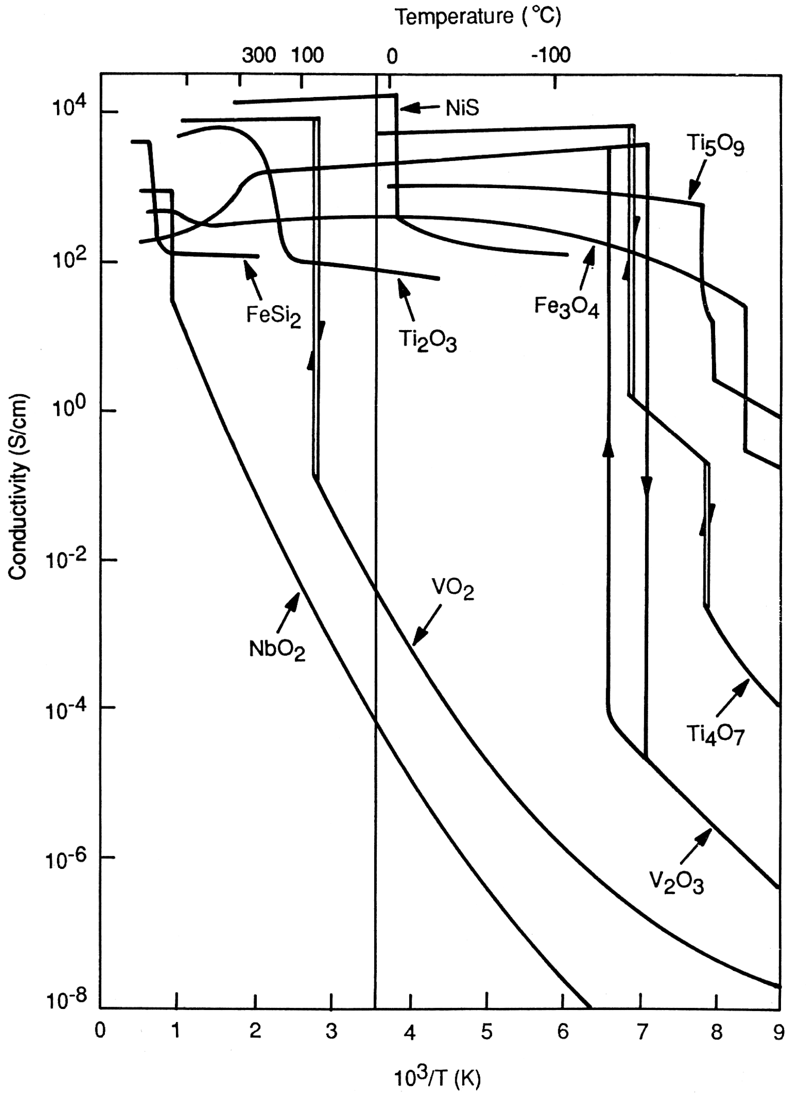
Thermochromism in VO_2



Low temperature:

- **Below 68 °C**
- **Semiconducting**
- **IR-transparent**
- **Monoclinic**

High temperature:

- **Above 68 °C**
- **Metallic**
- **IR-reflecting**
- **Tetragonal**

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Thermochromic VO_2 films: What are the issues?

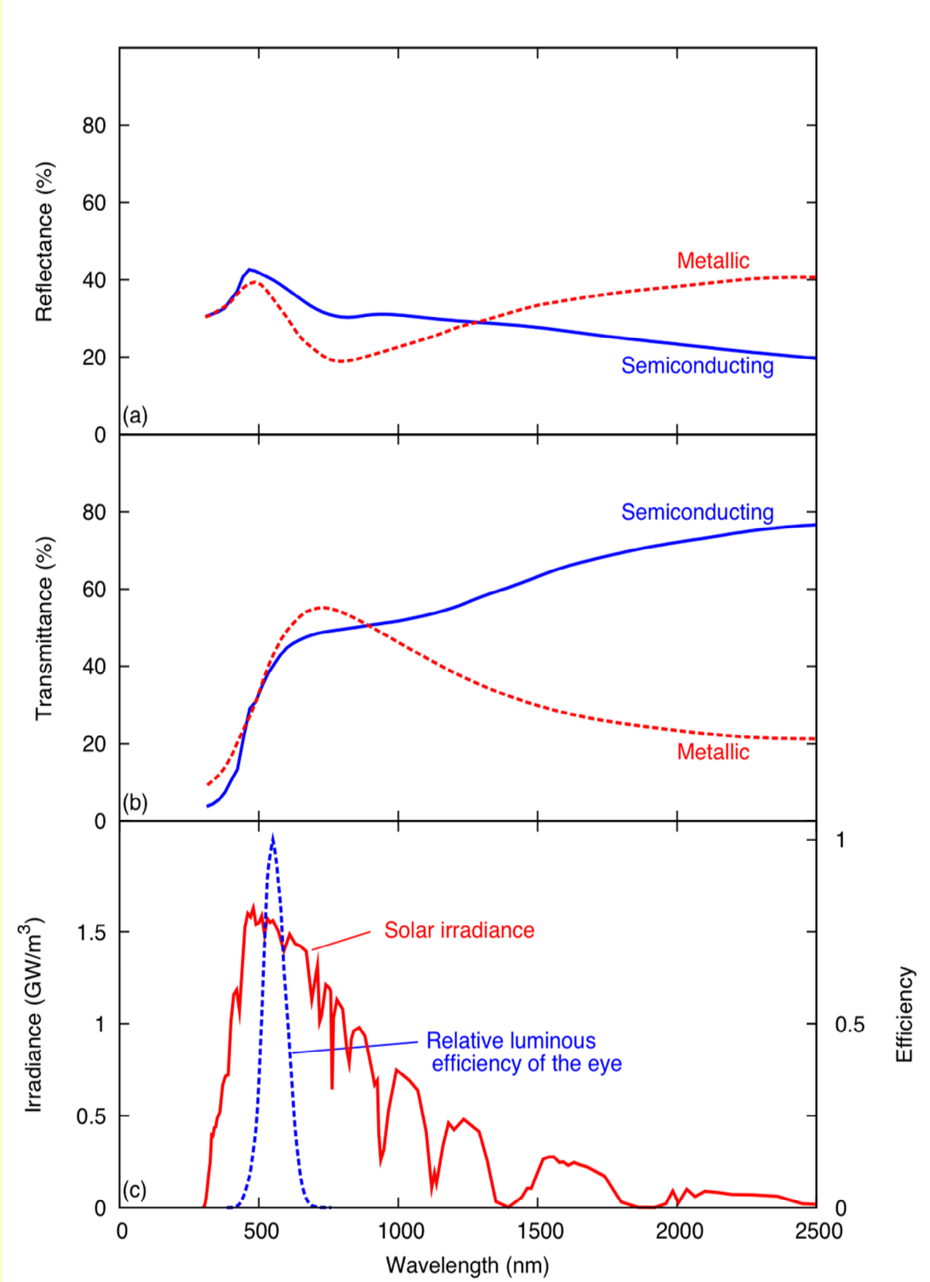
•Too high transition temperature.

•Dope with W!

•Too low luminous transmittance.

•Dope with Mg!

•Too low solar modulation. *Use nanoparticles!*



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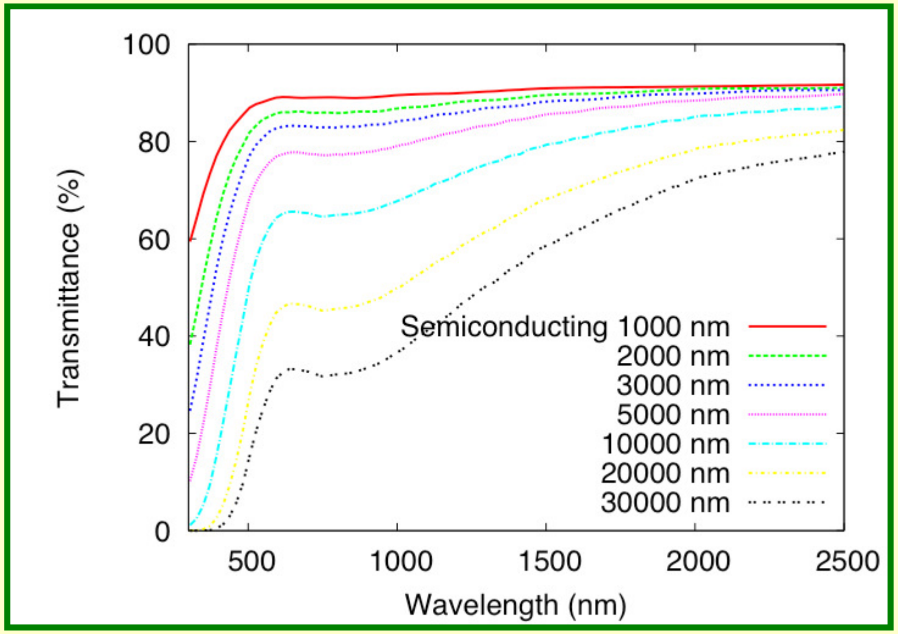
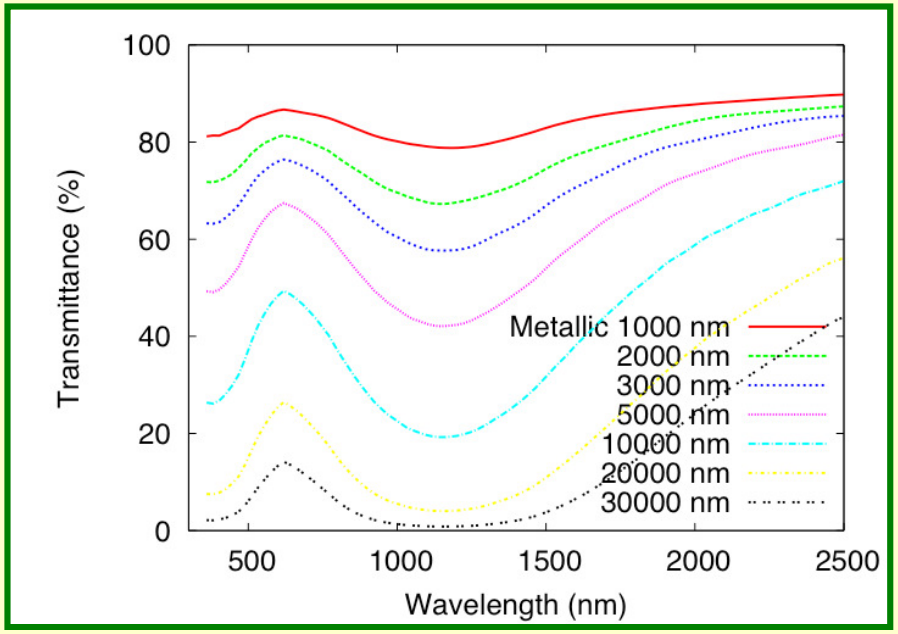
Thermochromism in VO_2 nanoparticles

1 vol% VO_2 in dielectric host

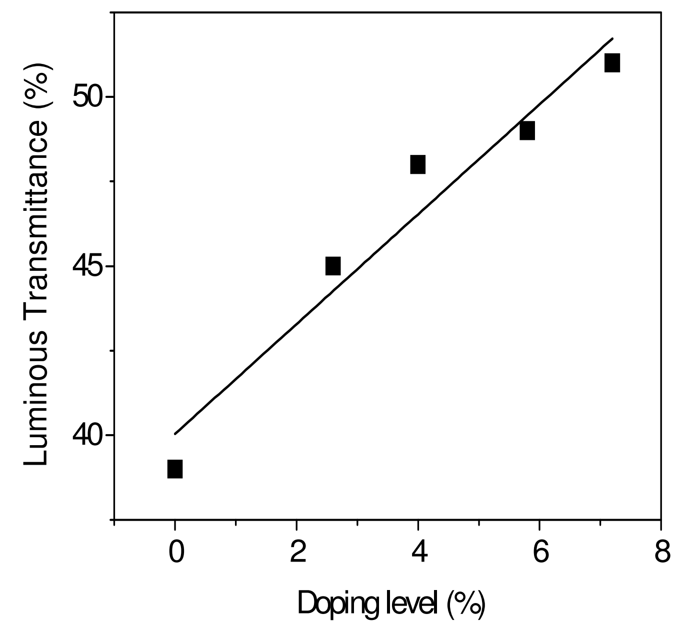
•Transparent
at low temperature

•NIR absorbing
at high temperature

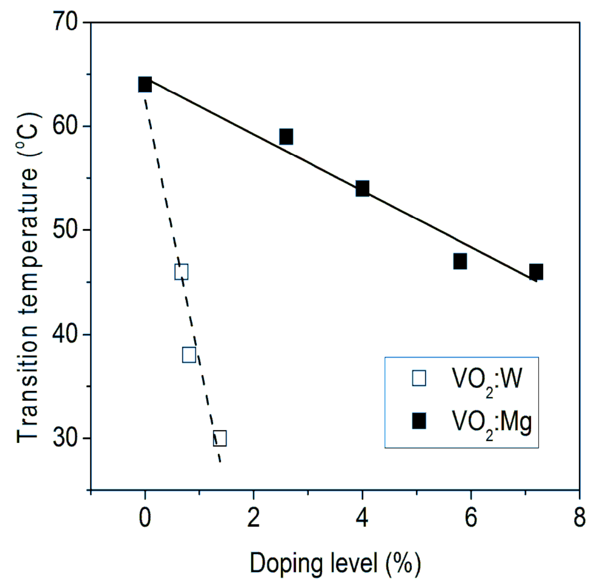




Optimization of VO_2 for window applications



Luminous transmittance is increased by Mg doping →



Transition temperature is decreased by W doping →

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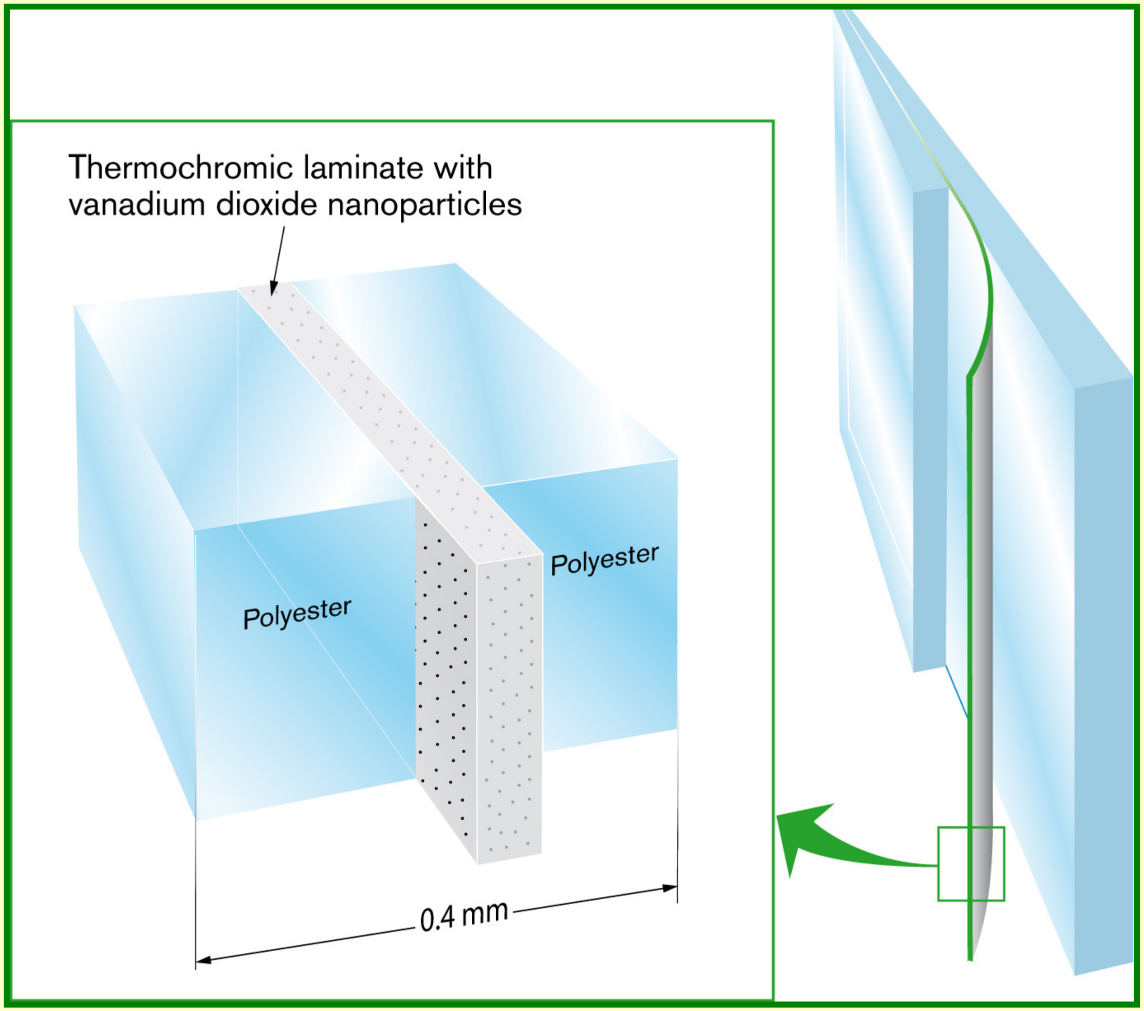
Possible implementation of nanothermochromism



The future of buildings??

Membrane architecture + EC foil

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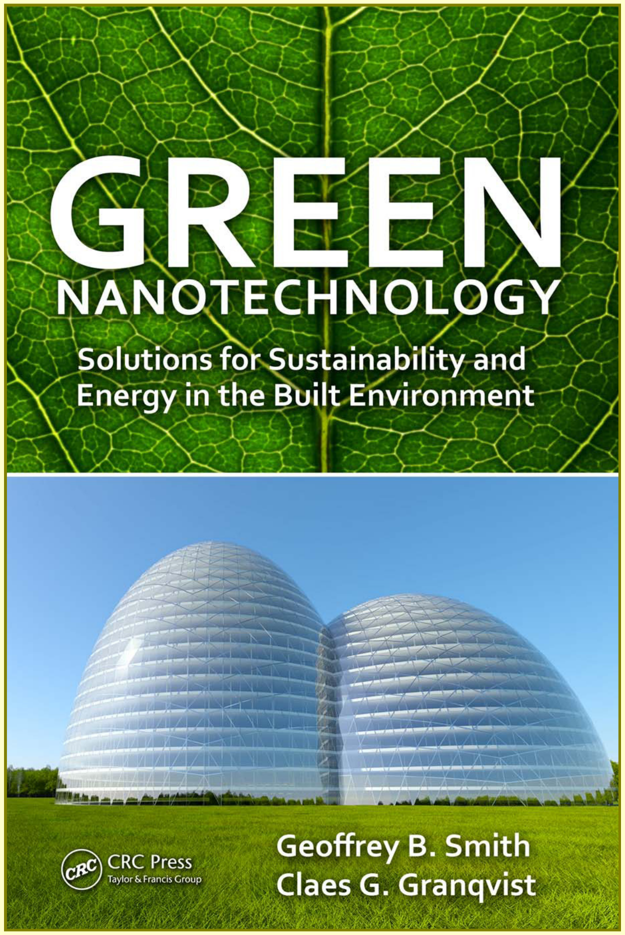
Towards a solution for the energy/CO_2 problem

Green NanoTechnology:



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