Lab #3
Transparent Conductors

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Sept. 23, 2014

PHYS 4580, 6/7280

Today at 4:30 pm, R1 Room 1010

Special Colloquium
UT Wright Center for PVIC/SSARE

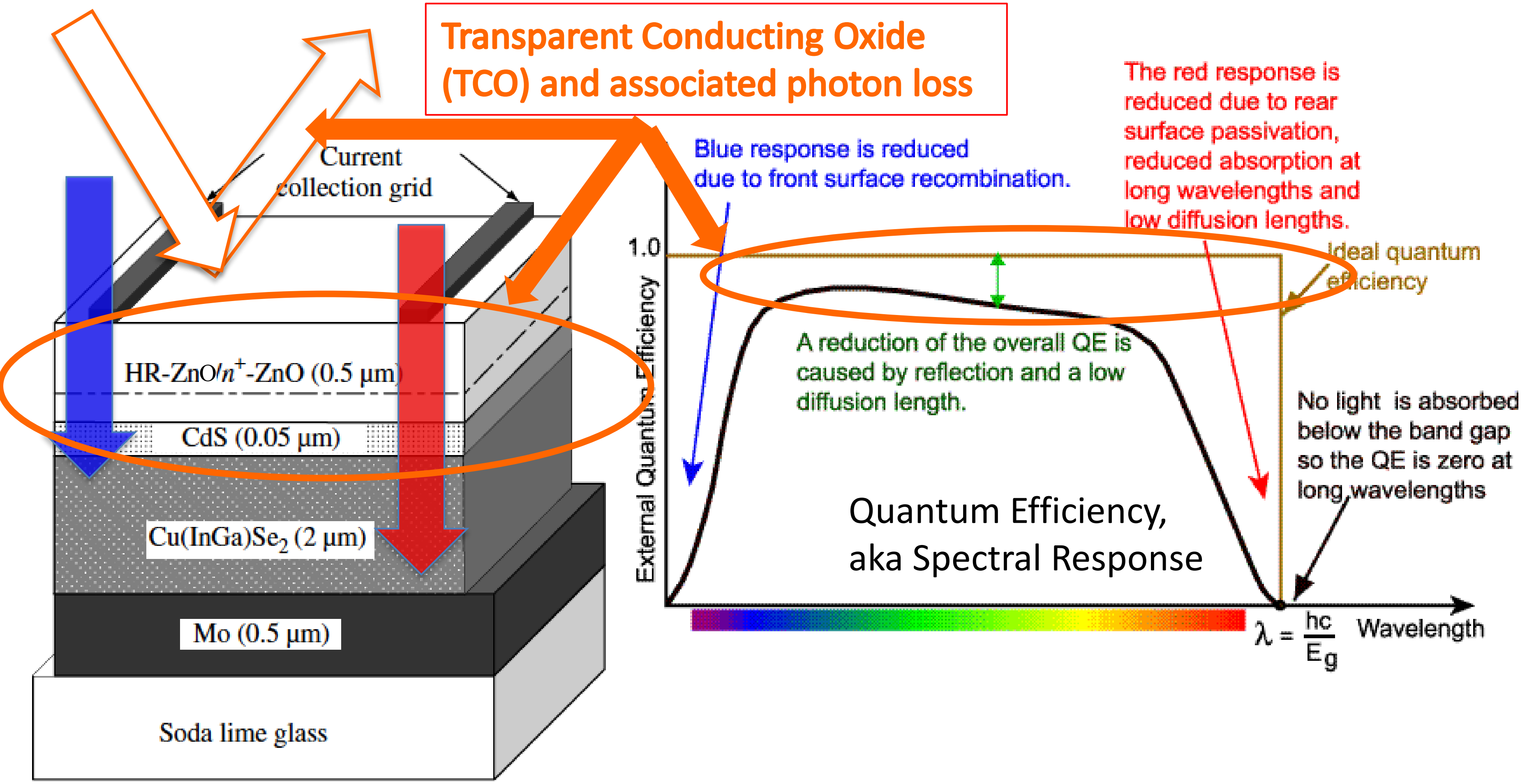
Photovoltaic Performance and Reliability at the Module Scale

Dr. Timothy Silverman

National Renewable Energy Laboratory

The presentation will summarize results from four different studies in PV performance and reliability, highlighting issues that emerge at the module scale. Topics to be discussed include the apparently positive P_{mp} temperature coefficient for thin-film GaAs modules, challenges associated with achieving performance stabilization for polycrystalline thin-film PV modules without light, the development of mechanical loading as a fast substitute for thermal cycling to determine the susceptibility to broken ribbons in crystalline Si modules, and the progress toward developing the capability for predicting failure due to nonuniform devices and illumination.

Impact of Optical Loss in Window Layer in PV Cells



Transparent Conducting Oxide (TCO) and associated photon loss

Blue response is reduced due to front surface recombination.

The red response is reduced due to rear surface passivation, reduced absorption at long wavelengths and low diffusion lengths.

A reduction of the overall QE is caused by reflection and a low diffusion length.

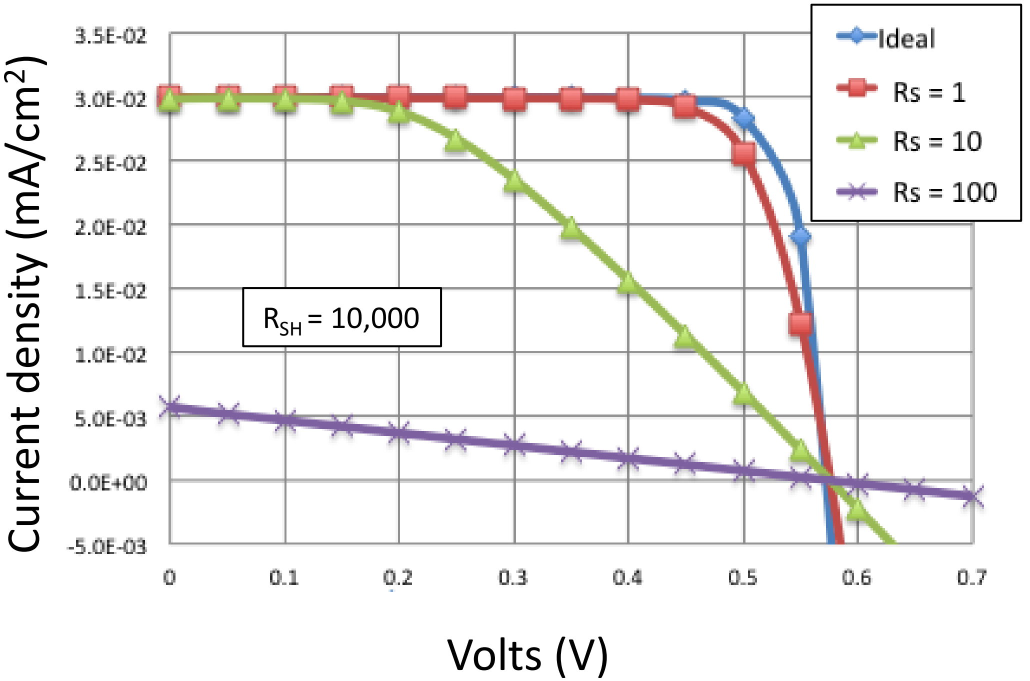
No light is absorbed below the band gap so the QE is zero at long wavelengths

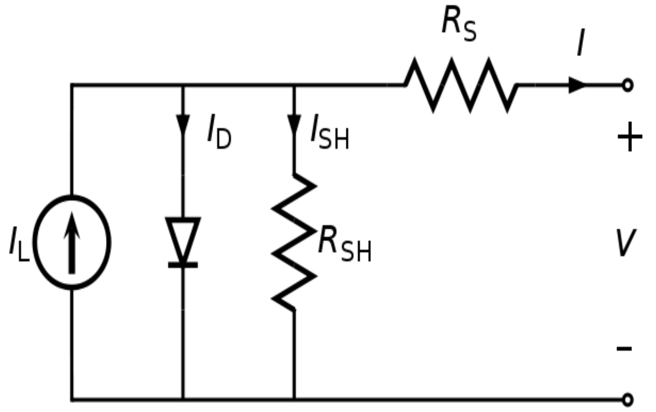
Quantum Efficiency, aka Spectral Response

Schematic cross section of a typical Cu(InGa)Se$_2$ solar cell

After"Cu(InGa)Se$_2$ Solar Cells", by Shafarman and Stolt, and *PVEducation.org*

Impact of Electrical Loss Due to High Series Resistance (R_S) PV cells

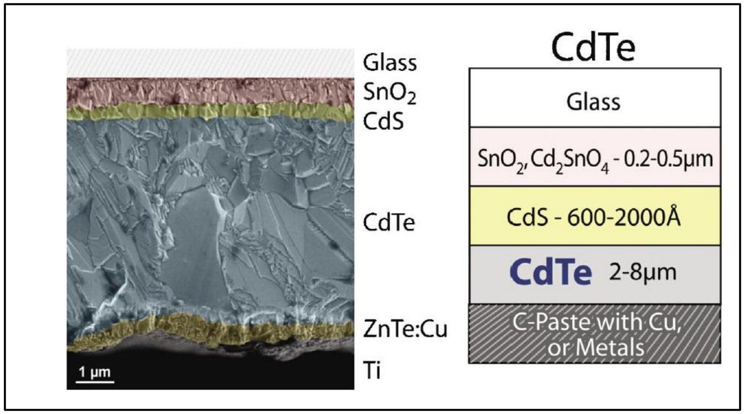


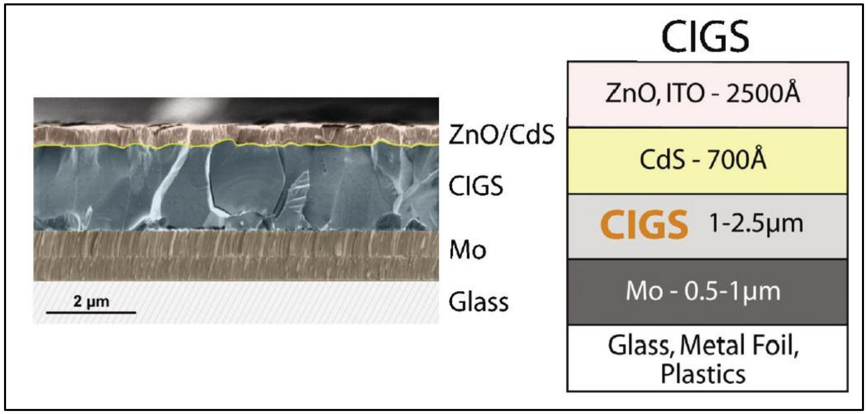


Diode equation with R_S and R_{SH}:

$$I = I_L - I_0 \exp\left[\frac{q(V + IR_S)}{nkT}\right] - \frac{V + IR_S}{R_{SH}}$$

TCOs are Used in *All* PV devices





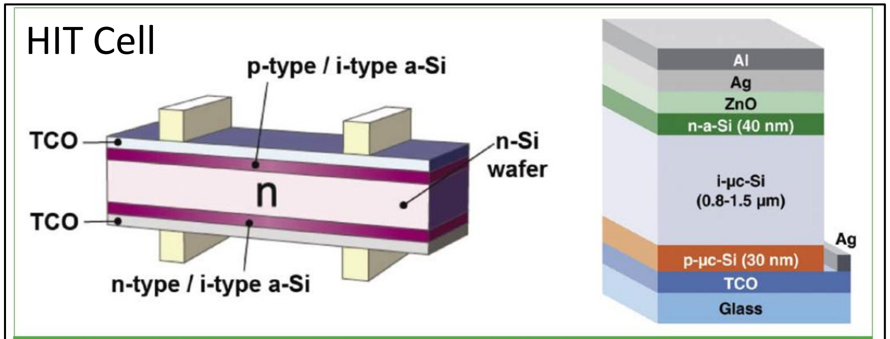


Figure 1. Configurations for Si heterojunction (SHJ) cells with Sanyo HIT cell on the left.

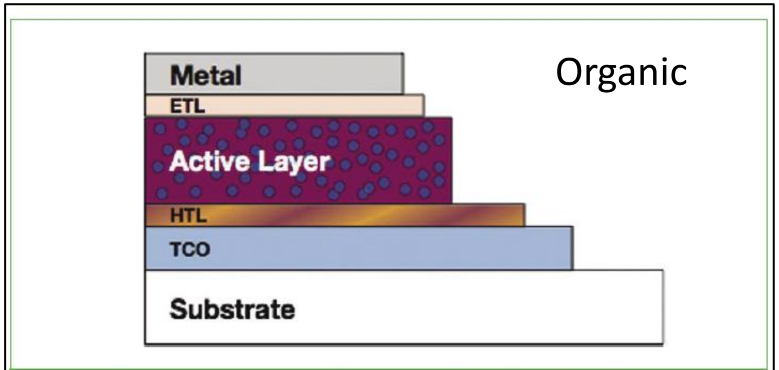


Figure 9. Schematic cross-section of an organic photovoltaic (OPV).

From:

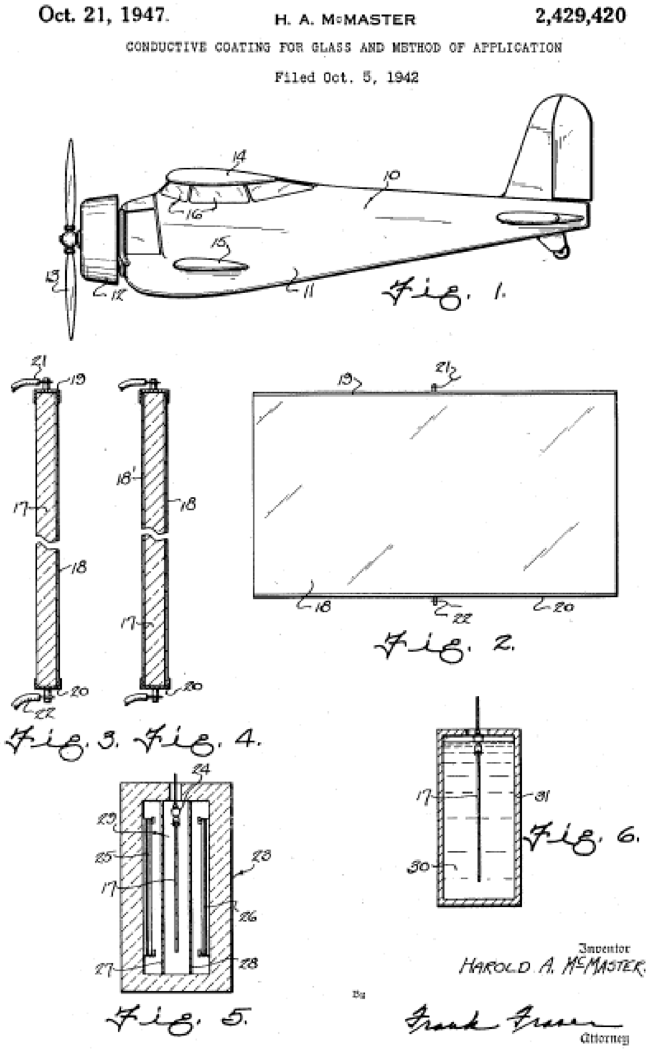
Transparent conducting oxides for advanced photovoltaic applications

John D. Perkins & **David S. Ginley**, National Renewable Energy Laboratory, Golden, Colorado, USA

This paper first appeared in the third print edition of *Photovoltaics International* journal.

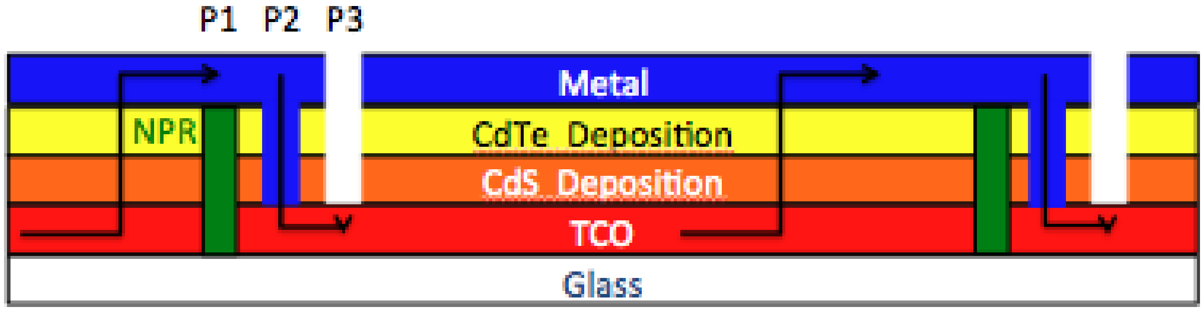
Long History of TCO R&D

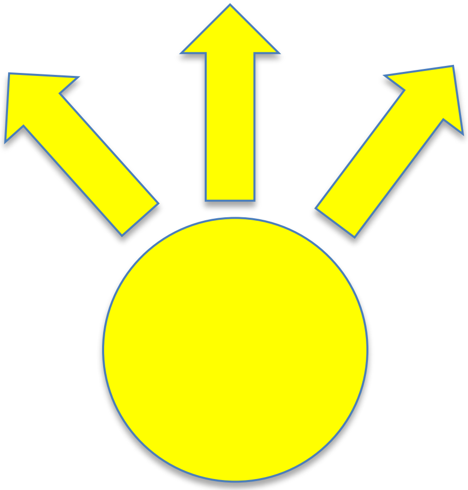
"It is an object of this invention to provide on glass or other electrically non-conductive surfaces thin transparent coatings or films possessing the property of electrical conductivity, which coatings are clear, hard and tenacious and of uniform thickness; which are in intimate contact with the glass or other surface; and which will retain these properties under adverse conditions" – *Harold McMaster*



Monolithically Integrated TF Module

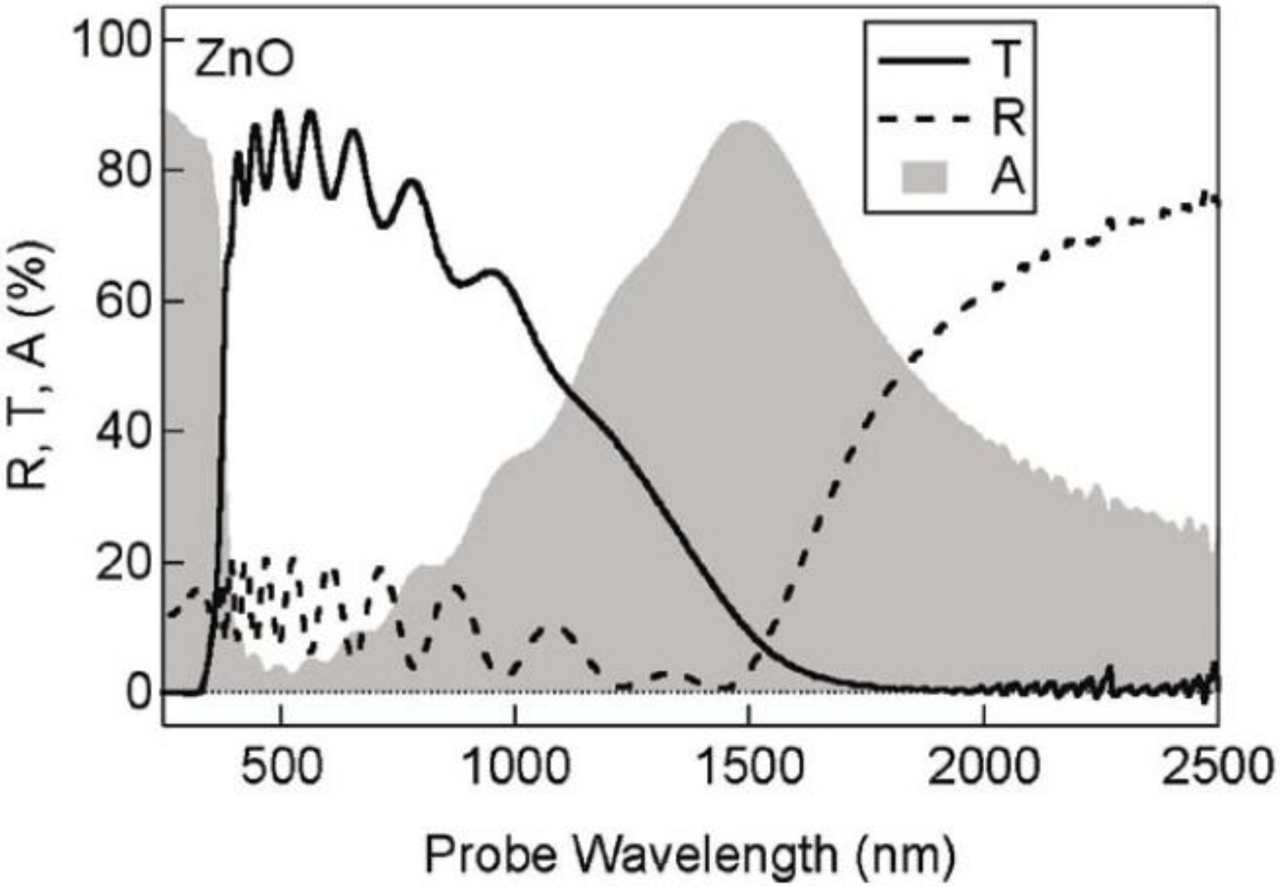
_The balance between electrical conductivity and optical transparency becomes even more important when current and photons are to be collected over large areas, as is the case in a module._*





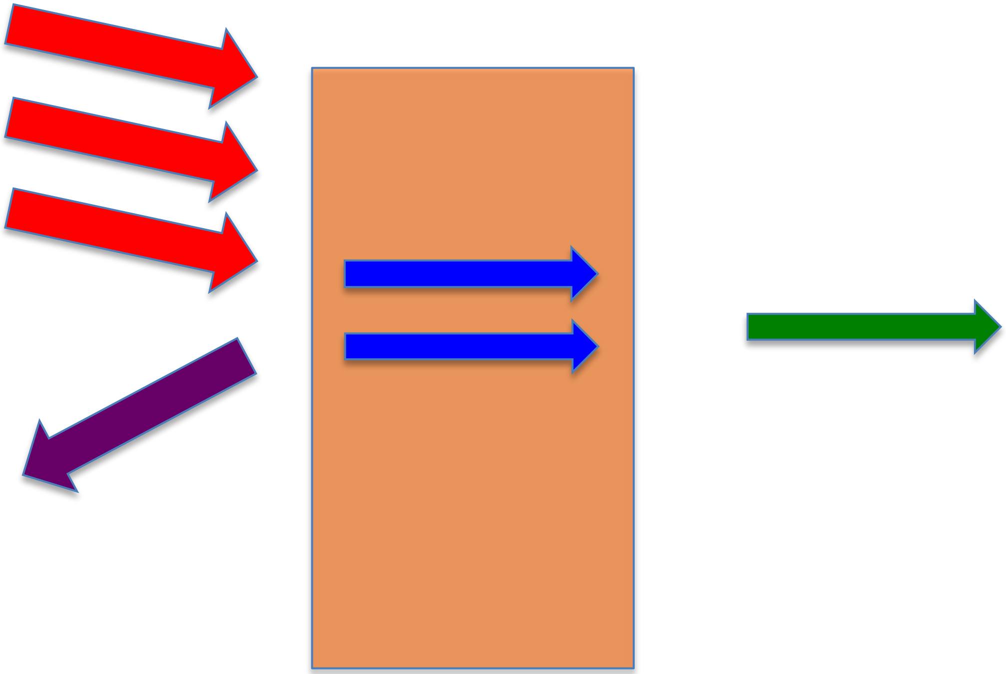
* Manufacturability is also a big concern!!

Typical Reflection, Transmission, and Absorption Data



From: Perkins and Ginley

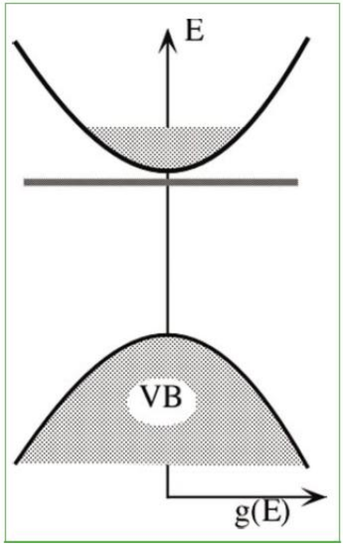
Total Incident (λ) = A(λ) + T(λ)+ R(λ)

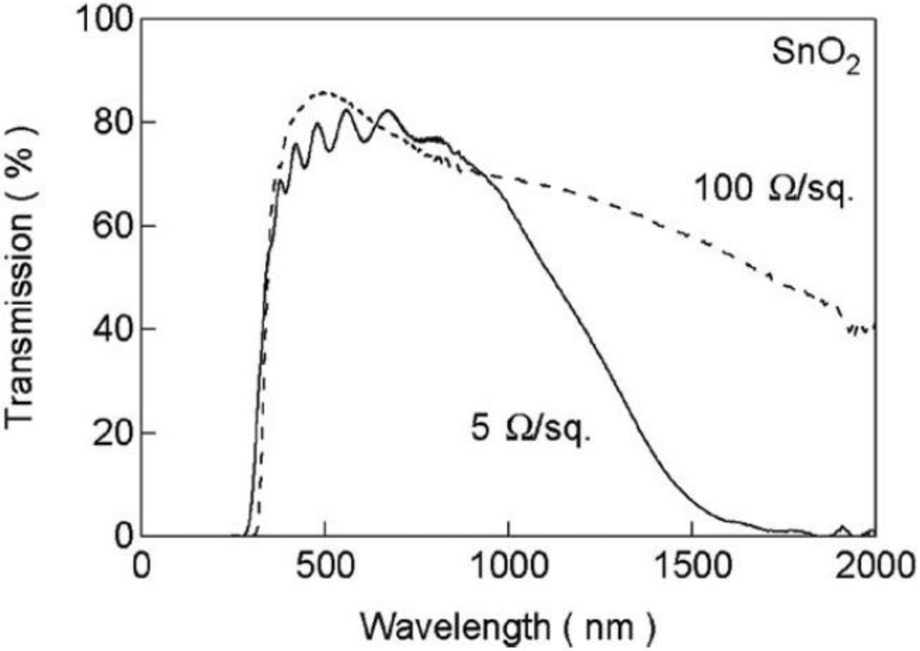


Conservation of Energy for each wavelength

Defect Equilibria and Doping in TCOs

- TCO materials are typically wide band gap oxides that are degeneratively doped via defect or substitutional chemistry.
- The trade off between electrical conductivity and transparency is due to the interplay between the electronic structure of the material and the doping.





From: Perkins and Ginley

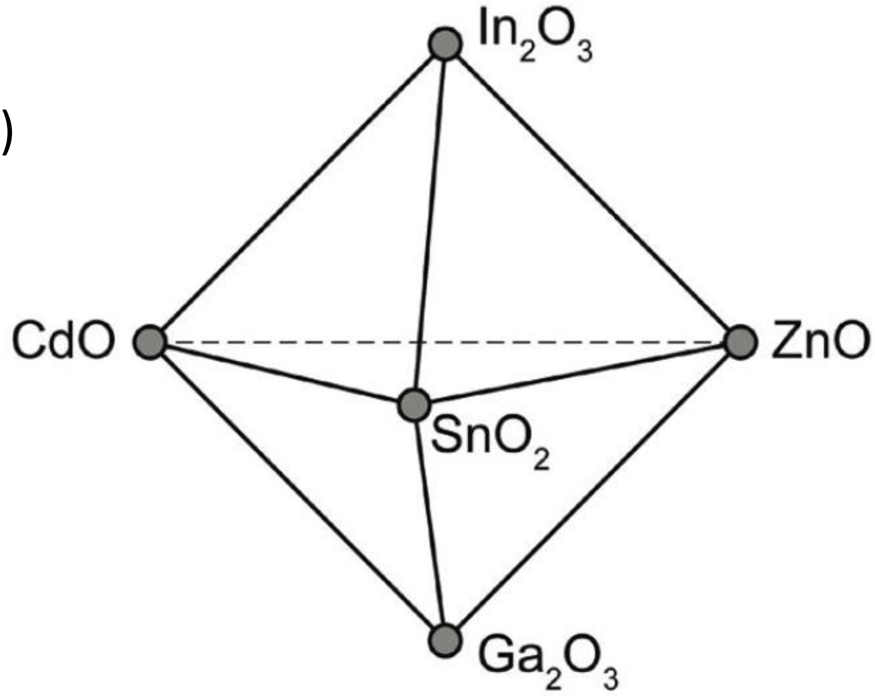
Phase Space for Engineering the Properties of TCOs

Additional Parameters for control:

- Compositional alloys (e.g. Cd_2SnO_4)
- Dopants on the anion sublattice (i.e. FTO)
- Dopants on the cation sublattice (e.g., IT0)
- Defect equilibria on oxygen subattice
- New materials
- Nanomaterials (non-oxides, e.g. single-wall carbon nanotubes, metal nano wires, composites, etc.

$$O_O^x \leftrightarrow V_O^{\bullet\bullet} + 0.5O_2(g) + 2e'$$

“Conventional” compositional space

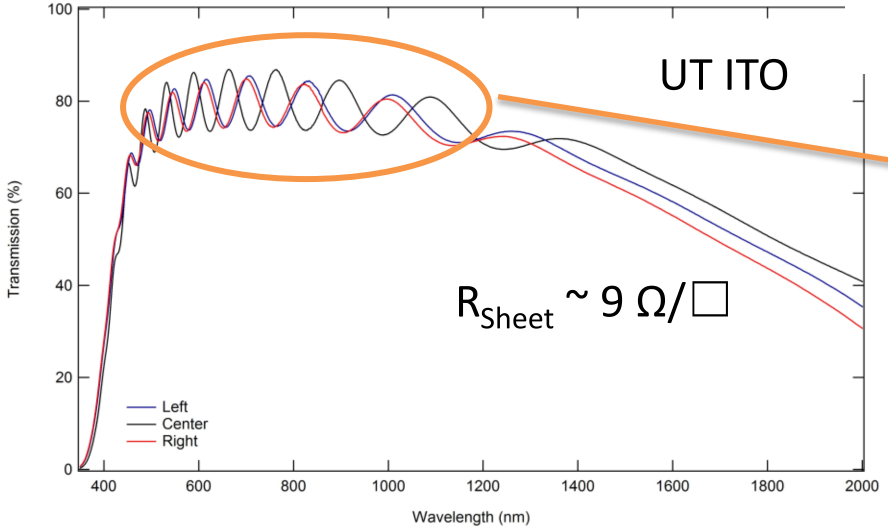


From: Perkins and Ginley

ITO – Tin doped Indium Oxide

$$2n_{\text{coating}} d \cos(\theta_2) = m\lambda$$ for constructive interference

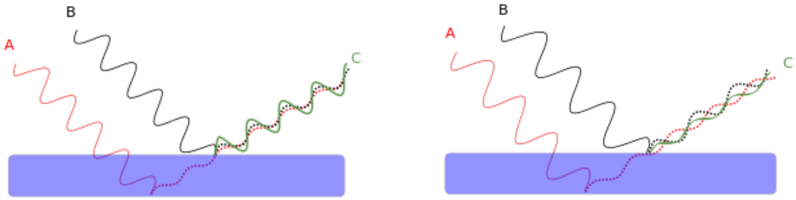
$$2n_{\text{coating}} d \cos(\theta_2) = \left(m - \frac{1}{2}\right)\lambda$$ for destructive interference



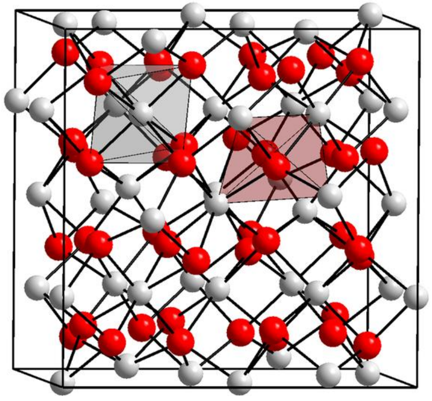
UT ITO

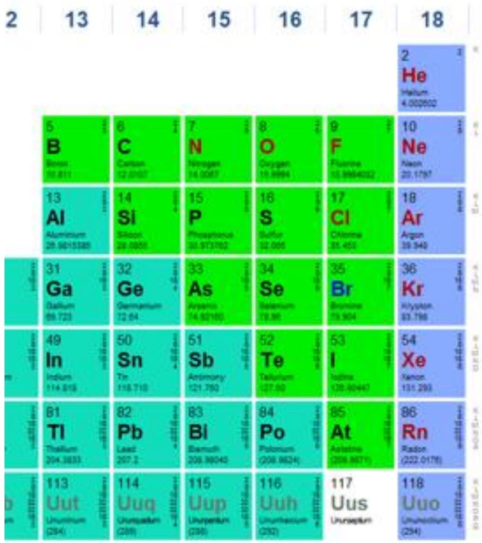
R_{Sheet} ~ 9 Ω/☐

Courtesy of *A. Phillips*



In$_2$O$_3$





http://en.wikipedia.org/wiki/Thin-film_interference

Snell’s Law and the Index of Refraction

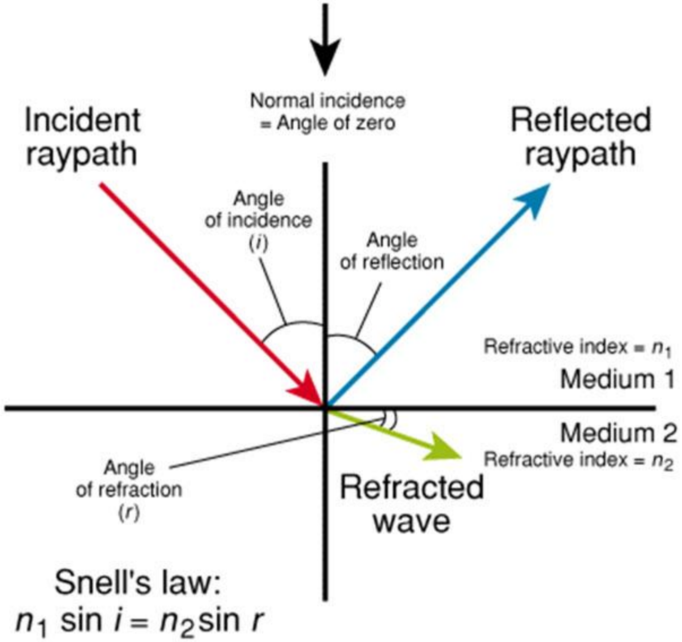
n, the Index of Refraction, *aka* Refractive Index

- Describes how light propagates in a medium.
- Is a dimensionless number.
- The speed of light in a medium is reduced:

$$\mathrm{v}_{ph} = \frac{c}{n} \qquad \nu = \frac{c}{\lambda}$$

$$\lambda = \frac{\lambda_0}{n}$$

Where λ_0 is the wavelength in vacuum



Although named after Dutch astronomer **Willebrord Snellius** (1580–1626), the law was first accurately described by the scientist **Ibn Sahl** at Baghdad court, when in 984 he used the law to derive lens shapes that focus light with no geometric aberrations in the manuscript *On Burning Mirrors and Lenses*

Absorption

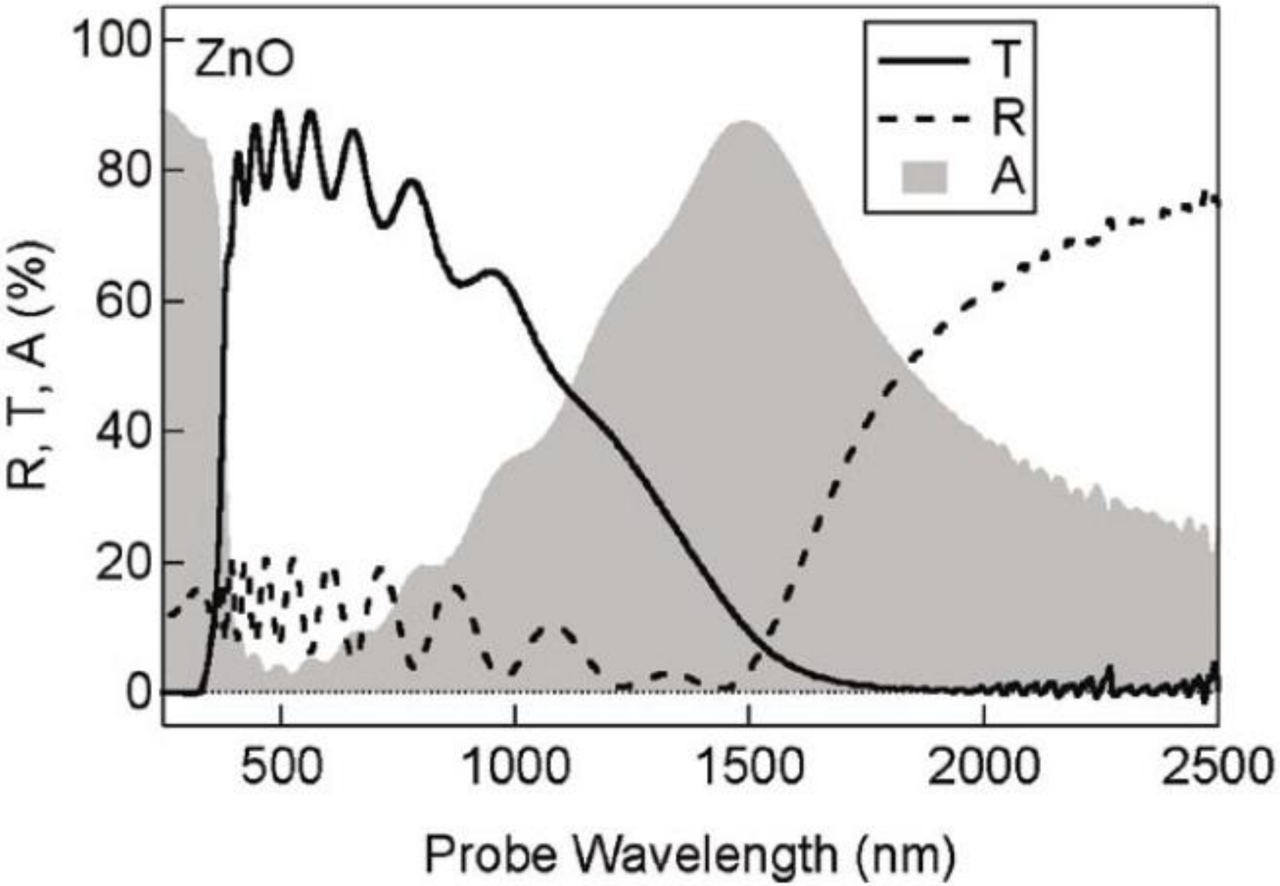
- Up to now, we have considered only the Index of Refraction, n.
- This is enough when there is no absorption (e.g., wide band gap oxides interacting with sub-band gap light).
- In general, we must consider refraction, reflection and and absorption, and a complex index:

$$\tilde{n} = n + i\kappa$$

- Here, n is still the Index of Refraction, and reflects the phase speed of the light in the medium, but *κ* now refers to the amount of absorption loss.

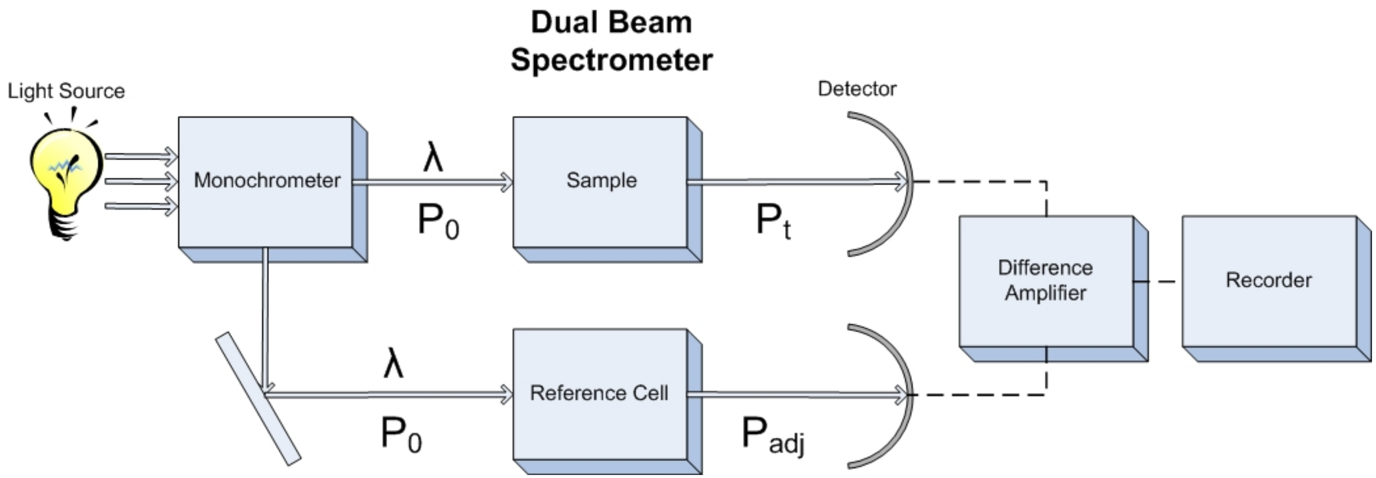
$$\alpha = \frac{4\pi\kappa}{\lambda} \qquad \frac{I}{I_0} = e^{-\alpha x}$$

Typical Reflection, Transmission, and Absorption Data



From: Perkins and Ginley

Conventional Dual Beam Spectrophotometer

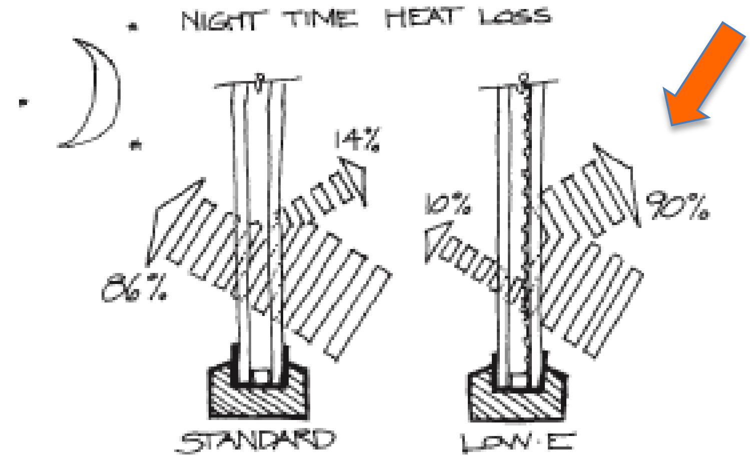


In this Lab, we are building a Single Beam Spectrophotometer

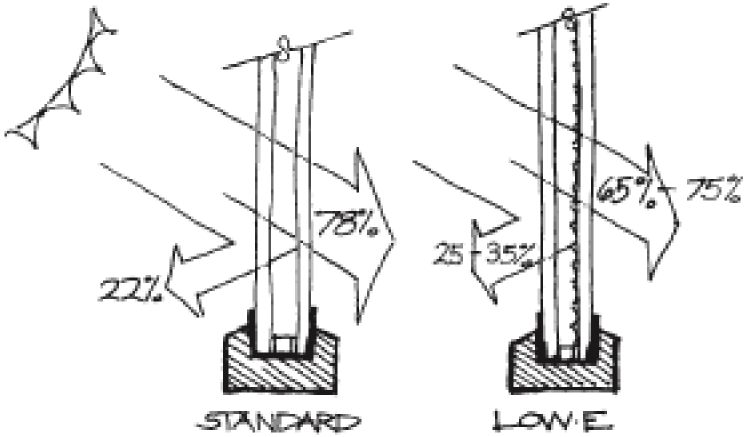
http://chemwiki.ucdavis.edu

TCO Coatings on Glass Facilitate High Efficiency window technology

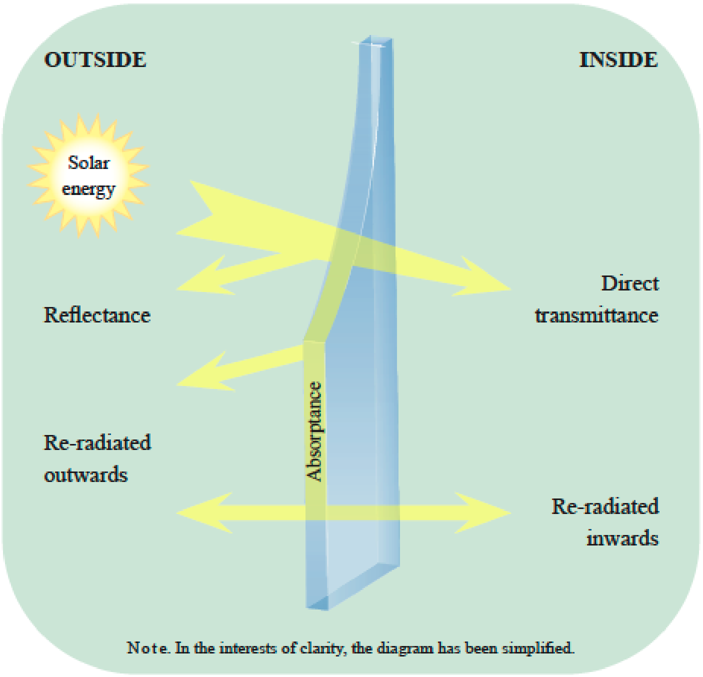
Reflection of long wavelength light at night is a big deal!



Reduction in Solar Passive Heat gain during the day



“Consumer’s guide to buying energy-efficient windows and doors” by Canada’s Office of Energy Efficiency



Note. In the interests of clarity, the diagram has been simplified.

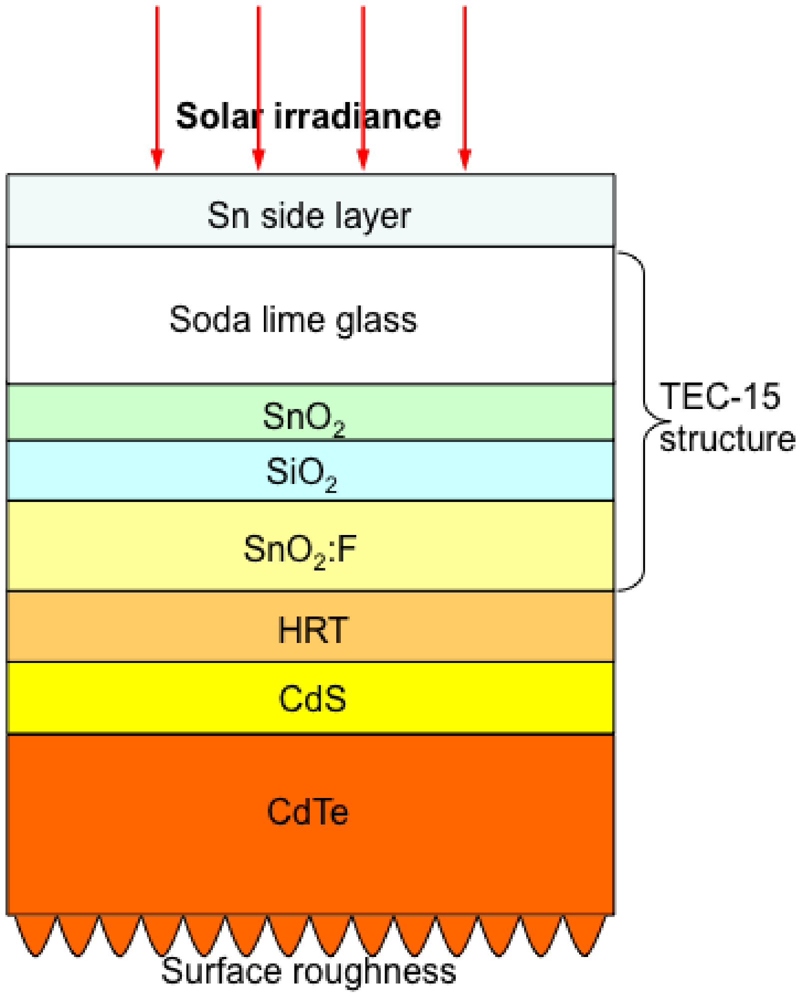
www.pilkington.com

Learn about how a Float Line Works at:
http://www.youtube.com/watch?v=OVokYKqWRZE

TEC Coatings are Complex

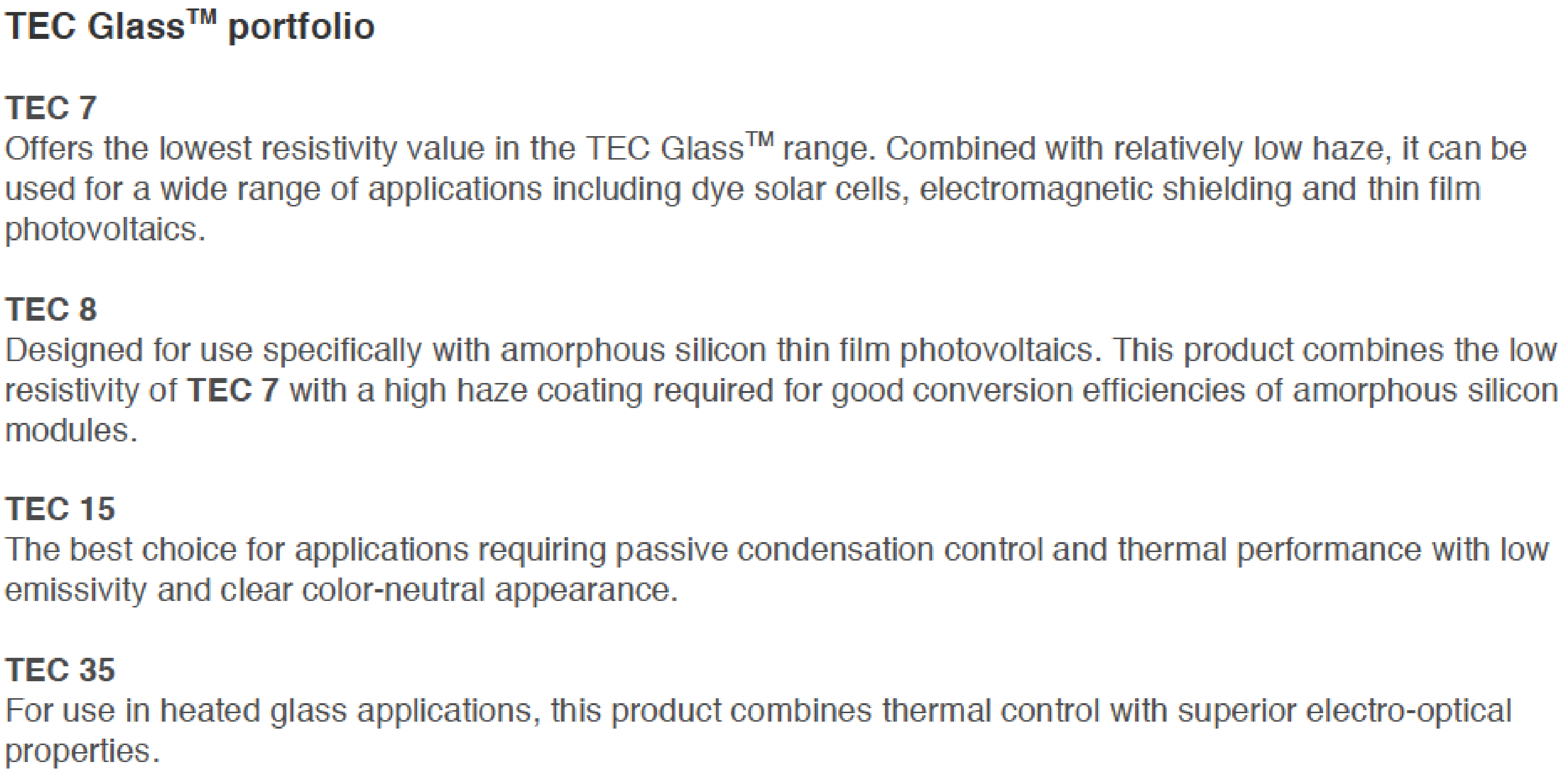
The TEC-15 glass:

- Thick soda-lime float glass (3.2 mm)
- Thin SnO_2 layer (~300 Å)
- SiO_2 layer (~200 Å)
- SnO_2:F layer (~3000 Å)
- Thick HRT (~850 Å)



Courtesy of Prakash Koirala

Different kinds of TEC products



TEC Glass$^{\text{TM}}$ portfolio

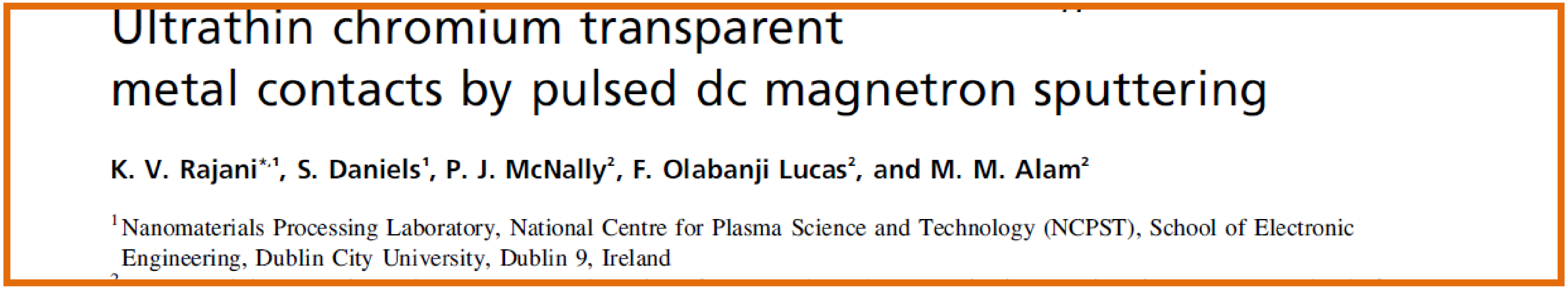
TEC 7
Offers the lowest resistivity value in the TEC Glass$^{\text{TM}}$ range. Combined with relatively low haze, it can be used for a wide range of applications including dye solar cells, electromagnetic shielding and thin film photovoltaics.

TEC 8
Designed for use specifically with amorphous silicon thin film photovoltaics. This product combines the low resistivity of **TEC 7** with a high haze coating required for good conversion efficiencies of amorphous silicon modules.

TEC 15
The best choice for applications requiring passive condensation control and thermal performance with low emissivity and clear color-neutral appearance.

TEC 35
For use in heated glass applications, this product combines thermal control with superior electro-optical properties.

http://www.cytodiagnostics.com

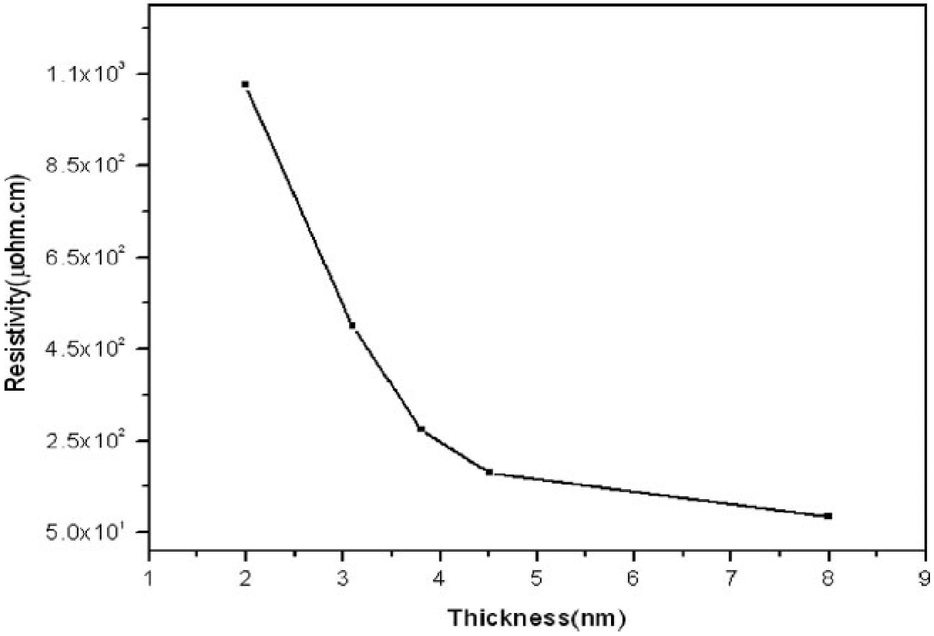


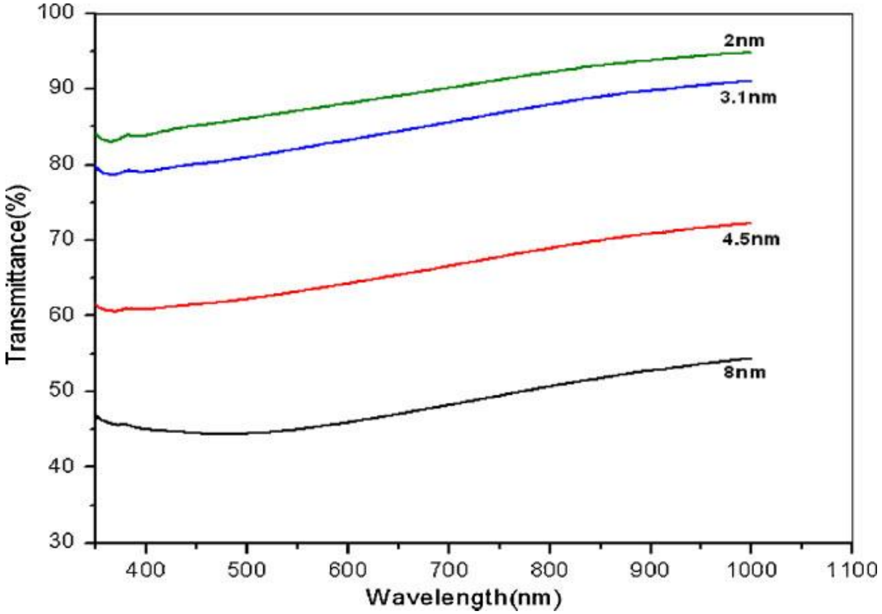
Ultrathin chromium transparent metal contacts by pulsed dc magnetron sputtering

K. V. Rajani[*,1], **S. Daniels**[1], **P. J. McNally**[2], **F. Olabanji Lucas**[2], **and M. M. Alam**[2]

[1] Nanomaterials Processing Laboratory, National Centre for Plasma Science and Technology (NCPST), School of Electronic Engineering, Dublin City University, Dublin 9, Ireland

Thin metal films can also be transparent

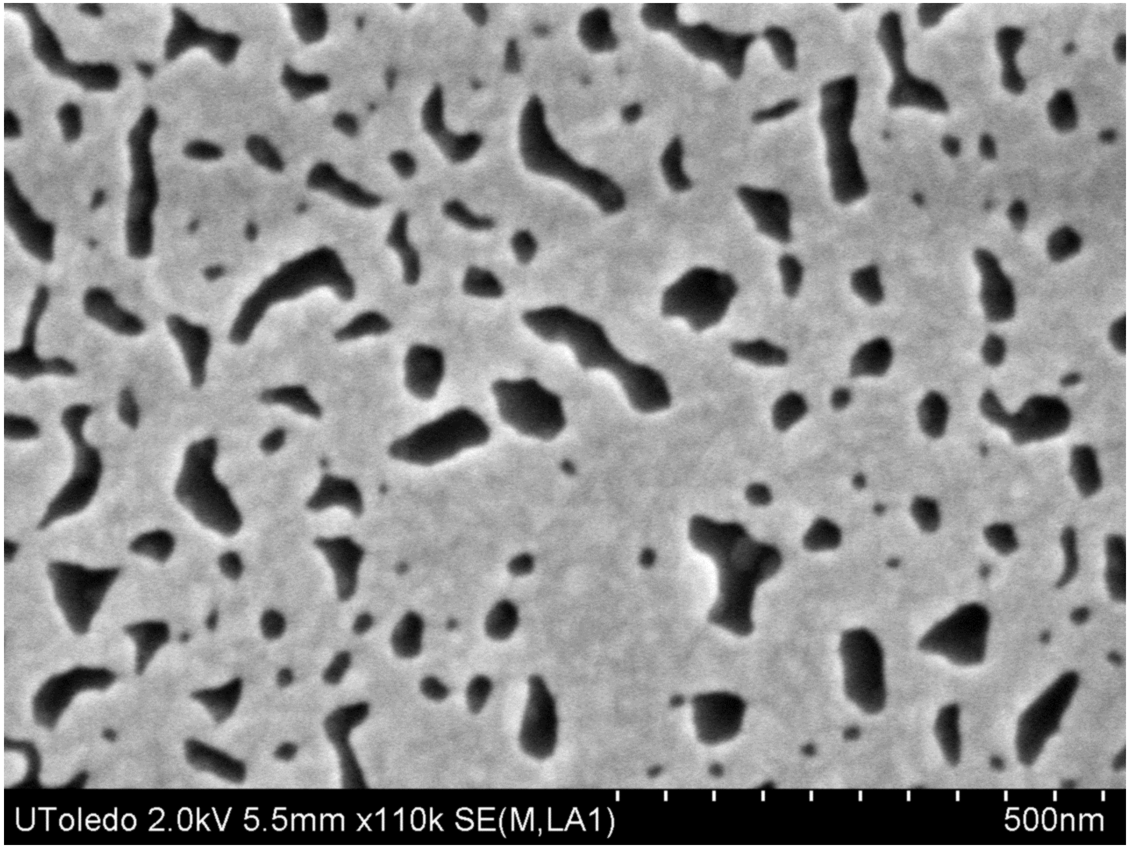




"The sheet resistance values corresponding to the 2, 3.1, 4.5 and 8 nm thick films are $5\text{x}10^3$, $1.6\text{x}10^3$, $4\text{x}10^2$ and $1\text{x}10^2$ Ω/□, respectively."

Phys. Status Solidi A **207**, No. 7, 1586–1589 (2010) / **DOI** 10.1002/pssa.200983732

Sheet Resistance – importance of film morphology



Scanning Electron Microscope (SEM) image of ~15 nm thick Au deposited by thermal evaporation.