Lab #3
Transparent Conductors

R.J. Ellingson and M.J. Heben

Sept. 17, 2013
PHYS 4580, 6/7280
Impact of Optical Loss in Window Layer in PV Cells

Transparent Conducting Oxide (TCO) and associated photon loss

Quantum Efficiency, aka Spectral Response

Schematic cross section of a typical Cu(InGa)Se₂ solar cell

After “Cu(InGa)Se₂ 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.

**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 ($\lambda$) = $A(\lambda) + T(\lambda) + R(\lambda)$

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$_2$SnO$_4$)
- Dopants on the anion sublattice (i.e. FTO)
- Dopants on the cation sublattice (e.g., IT0)
- Defect equilibria on oxygen sublattice
- New materials
- Nanomaterials (non-oxides, e.g. single-wall carbon nanotubes, metal nano wires, composites, etc.

$$O^x_O \leftrightarrow V^\bullet\bullet_O + 0.5O_2(g) + 2e'$$

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

$R_{\text{Sheet}} \sim 9 \, \Omega/\square$

Courtesy of A. Phillips

$\text{In}_2\text{O}_3$

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:

\[ v_{ph} = \frac{c}{n} \quad v = \frac{c}{\lambda} \]

\[ \lambda = \frac{\lambda_0}{n} \]

Where \( \lambda_0 \) 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 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 \( \kappa \) now refers to the amount of absorption loss.

\[
\alpha = \frac{4\pi\kappa}{\lambda}
\]

\[
\frac{I}{I_0} = e^{-\alpha x}
\]
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

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

www.pilkington.com
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™ portfolio

TEC 7
Offers the lowest resistivity value in the TEC Glass™ 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
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 $5 \times 10^3$, $1.6 \times 10^3$, $4 \times 10^2$ and $1 \times 10^2 \, \Omega/\square$, respectively.”
Sheet Resistance – importance of film morphology

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