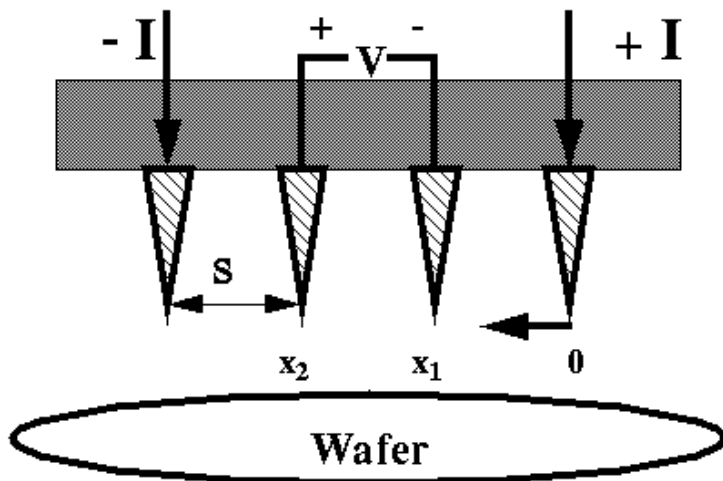# Transparent Conducting Films: Characterization of Electrical and Optical Properties

October 9, 2012
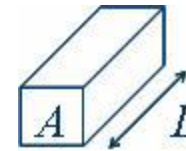
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Sheet Resistance

Regular 3-D conductor, resistance R is:

$$R = \rho \frac{L}{A} = \rho \frac{L}{Wt}$$

where ρ is the resistivity ($\Omega \cdot m$), A is the cross-section area, and L is the length. For A in terms of W and t,

$$R = \frac{\rho}{t} \frac{L}{W} = R_s \frac{L}{W}$$

where R_s is the <u>Sheet Resistance</u>. Units are ohms, but can also express this as "ohms per square, or $\Omega/\square$, or Ω/sq.

- A square sheet with an R_s of 100 $\Omega/\square$ has a resistance of 100 Ω (regardless of the size of the square).

Four point probe: Theory (bulk sample)

For a bulk sample (thickness t >> s, where s is the probe spacing), a spherical current from the outer probe tips is assumed:

Differential resistance given by: $\Delta R = \rho\left(\dfrac{dx}{A}\right)$

where ρ is the resistivity, dx is the differential length, and A is the surface area penetrated by the current from one probe.

To determine the resistance between the voltage measurement tips, one integrates between x_1 and x_2:

$$R = \int_{x_1}^{x_2} \rho\,\frac{dx}{2\pi x^2} = \frac{\rho}{2\pi}\left(-\frac{1}{x}\right)\Bigg|_{x_1}^{x_2} = \frac{1}{2s}\frac{\rho}{2\pi}$$
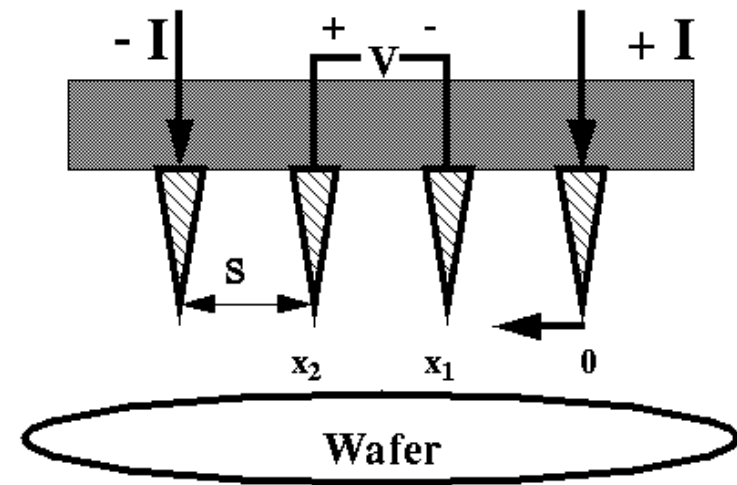
Superposition of current at outer two tips leads to R = V/2I, so that

V/2I = ρ /(4sπ) → ρ = 2πs(V/I)
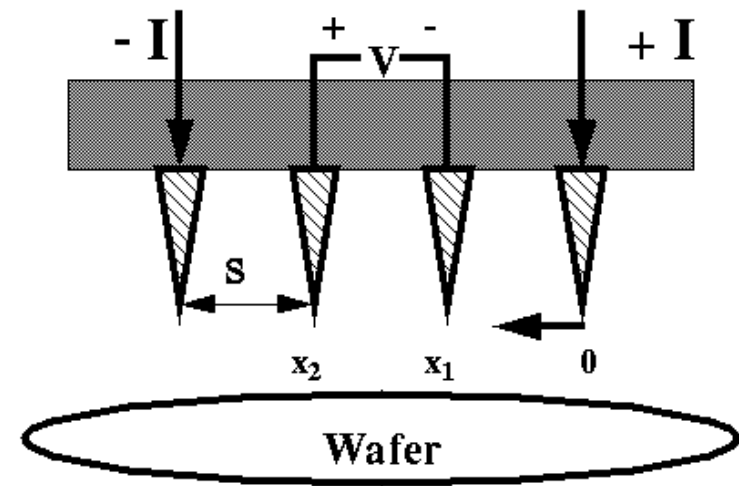
Four point probe: Theory (thin sheet)

For a thin film sample (thickness t << s), we have the case of current rings, so that A = 2πxt.

$$R = \int_{x_1}^{x_2} \rho \frac{dx}{2\pi x t} = \int_{s}^{2s} \rho \frac{dx}{2\pi x t} = \frac{\rho}{2\pi t} \left(\ln x \right) \Big|_{s}^{2s} = \frac{\rho}{2\pi t} \ln 2$$

As before, superposition of current at outer two tips leads to R = V/2I, so that the sheet resistivity for a thin film sample is:

$$\rho = \frac{\pi t}{\ln 2} \left(\frac{V}{I} \right)$$

Note that this expression is not dependent on s. *Sheet Resistivity* is defined as:

$$R_s = \frac{\rho}{t} = k \left(\frac{V}{I} \right)$$

k is a geometric factor, which for a semi-infinite thin film is π/(ln 2) = 4.53

Goals of the Transparent Conductors Unit

1) Use the optical system to measure the transmission, reflection and absorbance spectra from three Cr films and two TEC glass samples, at near-normal incidence.

2) Measure and report on the film thickness using the Dektak profilometer for the thickest Cr film. Based on your transmission measurements of all three Cr films, what do you predict as the thickness of the two thinner Cr films which you were unable to measure on the Dektak?

3) Use the four point probe to measure and report on the sheet resistance values for each of the five transparent conducting samples. For the Cr films, what do you predict as the thicknesses of the two thinner films based on the Dektak film thickness measurement for the thickest film and the sheet resistance values for all three films? Explain briefly how a film of (for example) half the thickness of another may not show a sheet resistance twice that of the thicker film.

4) Describe the interplay between transparency and sheet resistance for the 3 Cr film samples, and separately for the 2 TEC glass substrates.

5) Of the five films you have examined, which would function best as the top contact of a solar cell, and why?

Snell's Law:

$$\frac{\sin \theta_{\mathrm{i}}}{\sin \theta_{\mathrm{t}}} = \frac{n_2}{n_1}$$
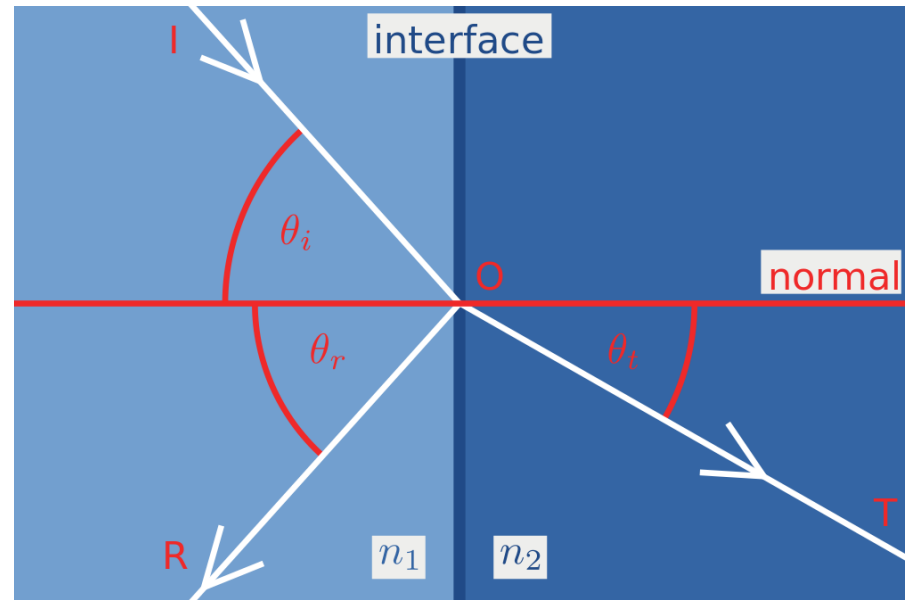
Polarized Light

Recall that the electric field direction of light is always perpendicular to the direction the light is traveling.

The incident light is *s*-polarized. That means its electric field is in the plane of the interface (perpendicular to the plane of the diagram above).

The incident light is *p*-polarized. That means its electric field is in a perpendicular direction to *s*-polarized above (in the plane of the diagram above).

Fresnel Coefficients

$$R_{\mathrm{s}} = \left| \frac{n_1 \cos\theta_{\mathrm{i}} - n_2 \cos\theta_{\mathrm{t}}}{n_1 \cos\theta_{\mathrm{i}} + n_2 \cos\theta_{\mathrm{t}}} \right|^2 = \left| \frac{n_1 \cos\theta_{\mathrm{i}} - n_2 \sqrt{1 - \left(\frac{n_1}{n_2}\sin\theta_{\mathrm{i}}\right)^2}}{n_1 \cos\theta_{\mathrm{i}} + n_2 \sqrt{1 - \left(\frac{n_1}{n_2}\sin\theta_{\mathrm{i}}\right)^2}} \right|^2$$

$$R_{\mathrm{p}} = \left| \frac{n_1 \cos\theta_{\mathrm{t}} - n_2 \cos\theta_{\mathrm{i}}}{n_1 \cos\theta_{\mathrm{t}} + n_2 \cos\theta_{\mathrm{i}}} \right|^2 = \left| \frac{n_1 \sqrt{1 - \left(\frac{n_1}{n_2}\sin\theta_{\mathrm{i}}\right)^2} - n_2 \cos\theta_{\mathrm{i}}}{n_1 \sqrt{1 - \left(\frac{n_1}{n_2}\sin\theta_{\mathrm{i}}\right)^2} + n_2 \cos\theta_{\mathrm{i}}} \right|^2$$