Lab #3
Transparent Conductors: Transparency, Conductivity, and Film Thickness

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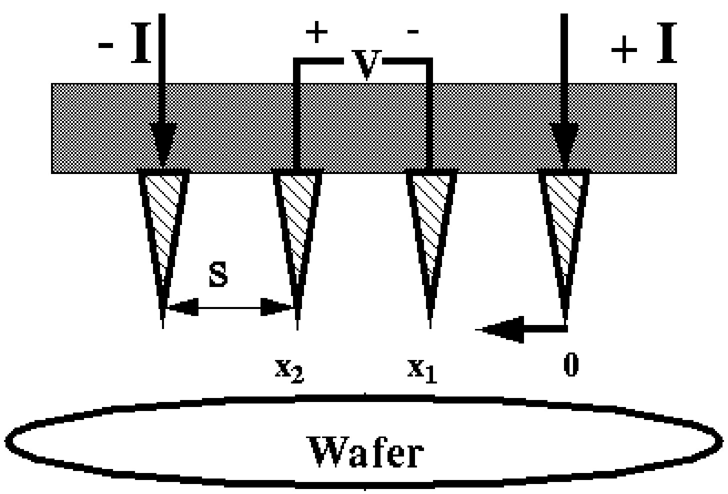
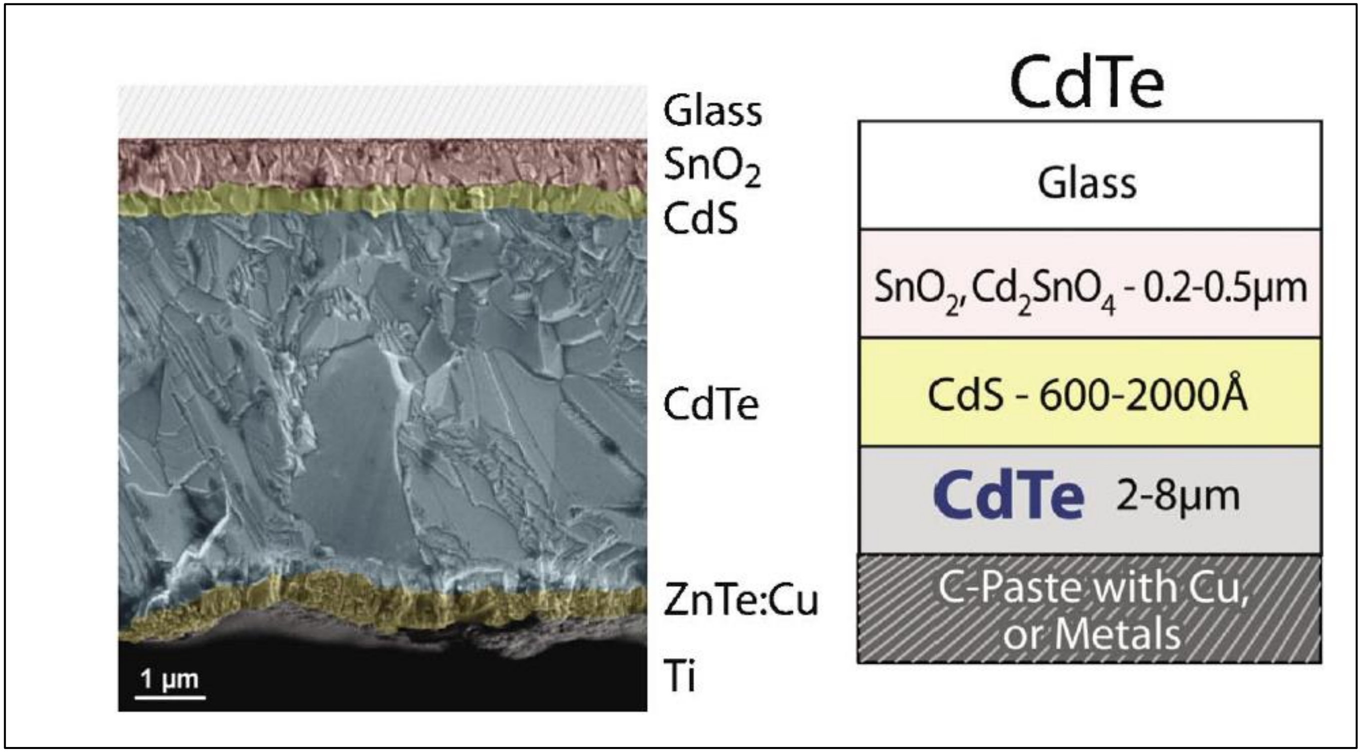


Sept. 30, 2014

PHYS 4580, 6/7280

TC layer: transmit light into the semiconducting layers, and transport charge out of the device



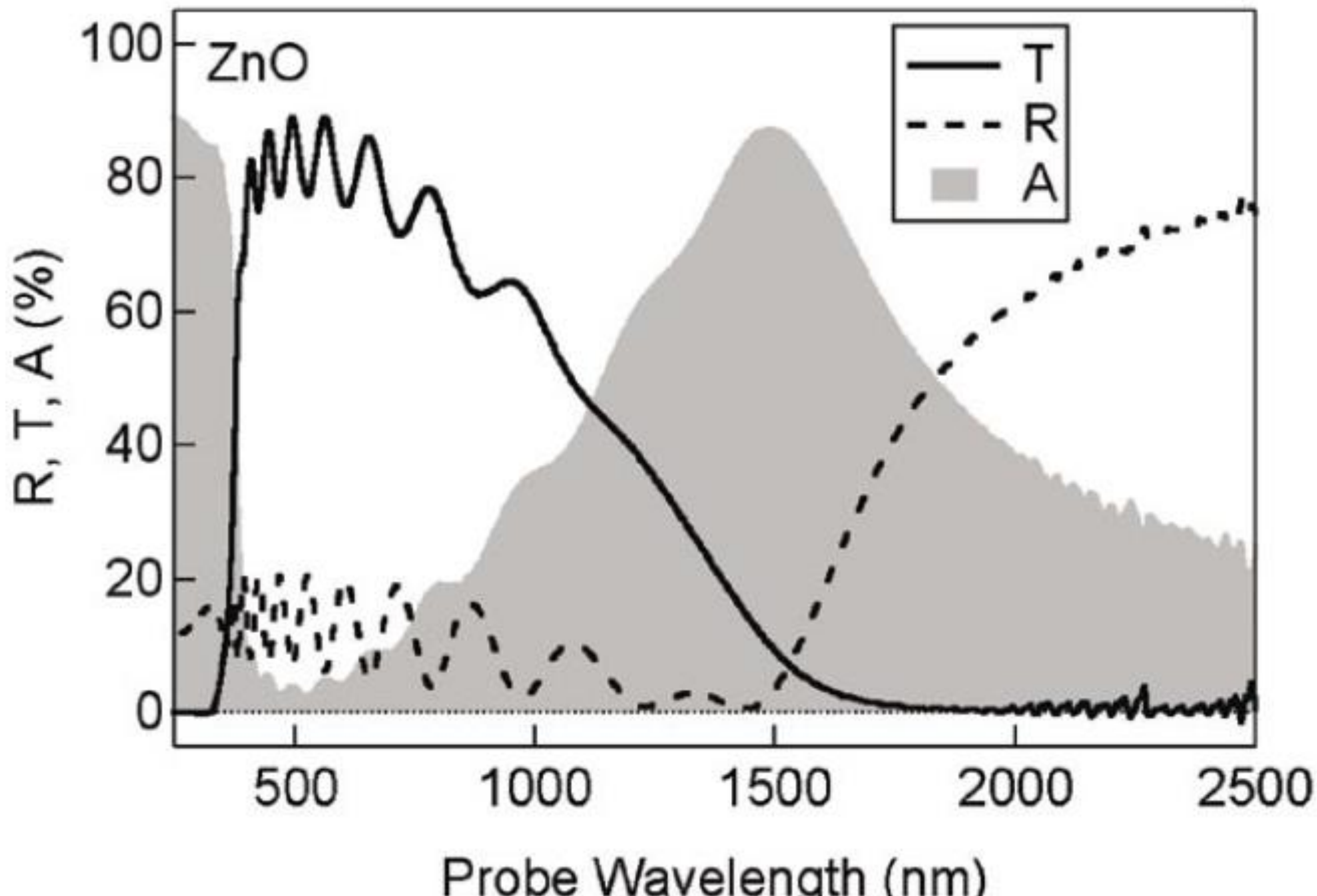
From:

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.

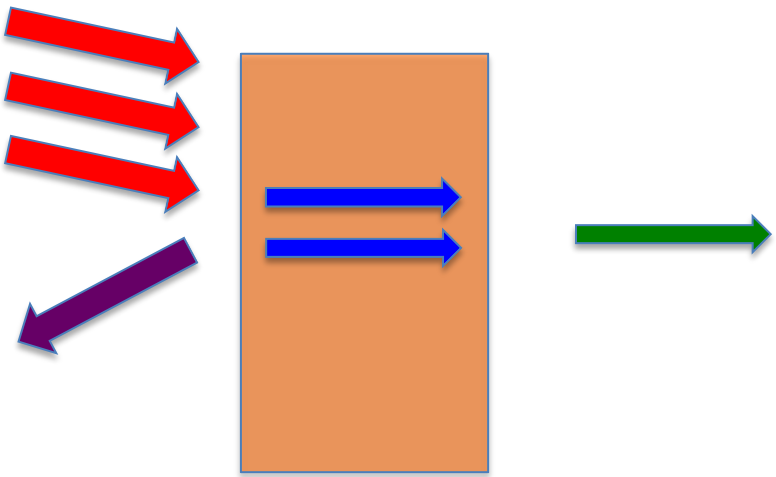
Typical Reflection, Transmission, and Absorption Data



From: Perkins and Ginley

$$\text{Total Incident } (\lambda) = A(\lambda) + T(\lambda) + R(\lambda)$$

$$1 = A(\lambda) + T(\lambda) + R(\lambda)$$



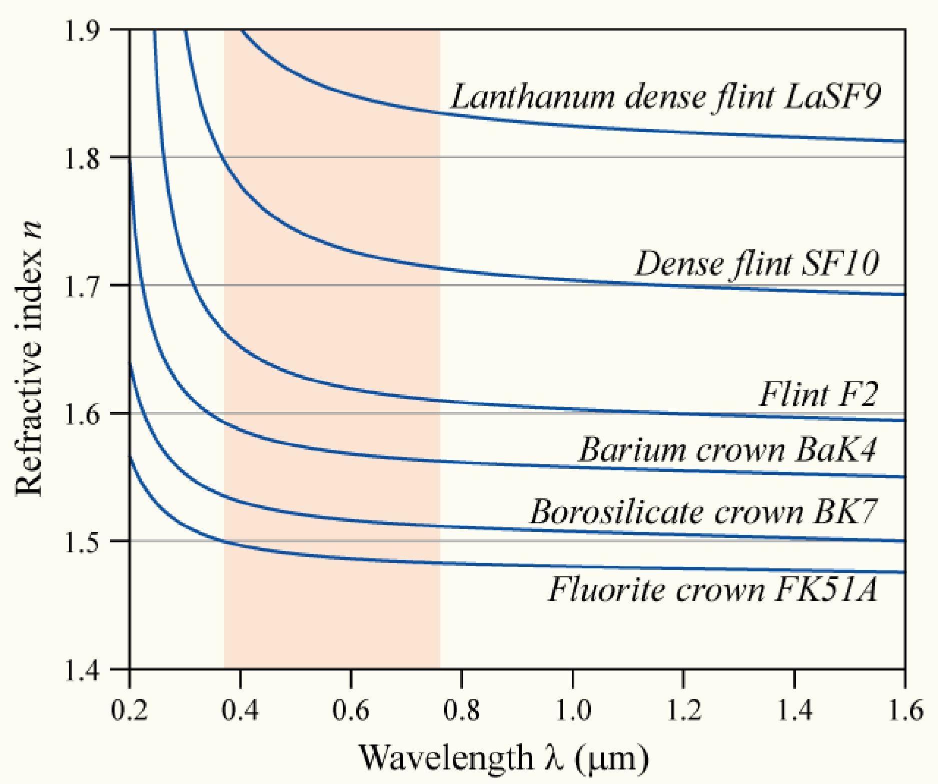
- Express Transmission, Reflection, and Absorption as values from 0 to 1: $0 \leq T \leq 1$, $0 \leq R \leq 1$, $0 \leq A \leq 1$.

Reflectance Measurements

For your reflectance measurements, note that the *dispersion* of glass between 300-1500 nm is not that large.

http://en.wikipedia.org/wiki/Dispersion_(optics)

The phase velocity of light, $v = c/n$, varies with λ when the refractive index n is a function of λ: $n = n(\lambda)$. For glass, $1 < n(\lambda_{red}) < n(\lambda_{yellow}) < n(\lambda_{blue})$.



$$R = \left| \frac{n_1 - n_2}{n_1 + n_2} \right|^2$$

~10% reflectance at $n_1 = 1$ and $n_2 = 1.9$

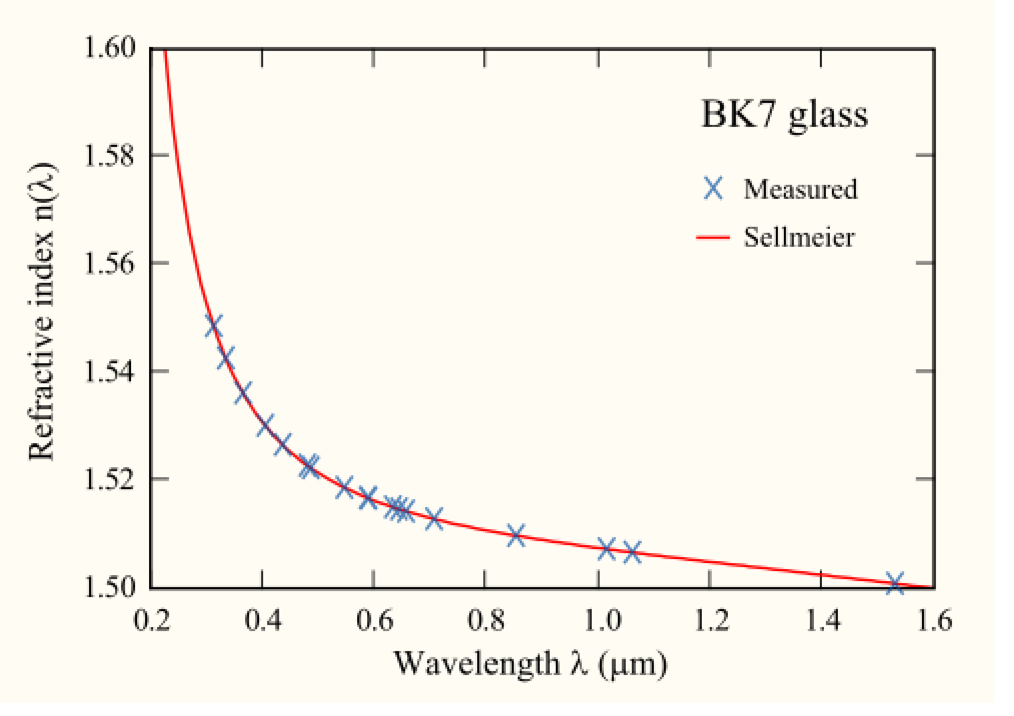
~4% reflectance at $n_1 = 1$ and $n_2 = 1.5$

Dispersion defined by Sellmeier equation

$$n^2(\lambda) = 1 + \frac{B_1\lambda^2}{\lambda^2 - C_1} + \frac{B_2\lambda^2}{\lambda^2 - C_2} + \frac{B_3\lambda^2}{\lambda^2 - C_3}$$

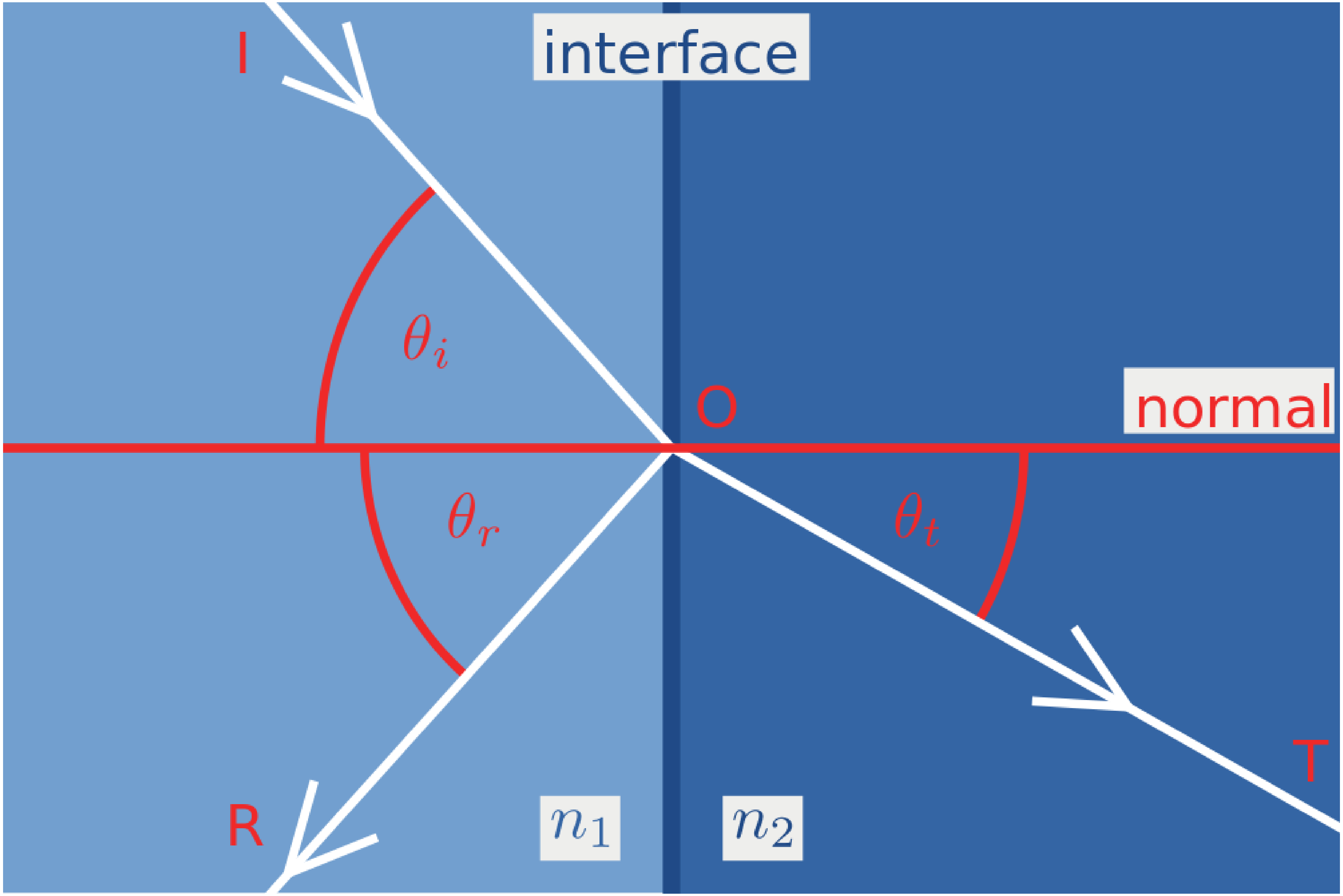
Example: the coefficients for a common borosilicate crown glass known as *BK7* are shown below:

Coefficient	Value
B_1	1.03961212
B_2	0.231792344
B_3	1.01046945
C_1	6.00069867×10^{-3} µm^2
C_2	2.00179144×10^{-2} µm^2
C_3	1.03560653×10^{2} µm^2



http://en.wikipedia.org/wiki/Sellmeier_equation

Fresnel Coefficients



http://en.wikipedia.org/wiki/Fresnel_equations

Fresnel Coefficients

S-Polarized Light has an Electric Field that is Normal to the Plane of Travel

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

P-polarized Light has an Electric Field that is Parallel to the Plane of Travel

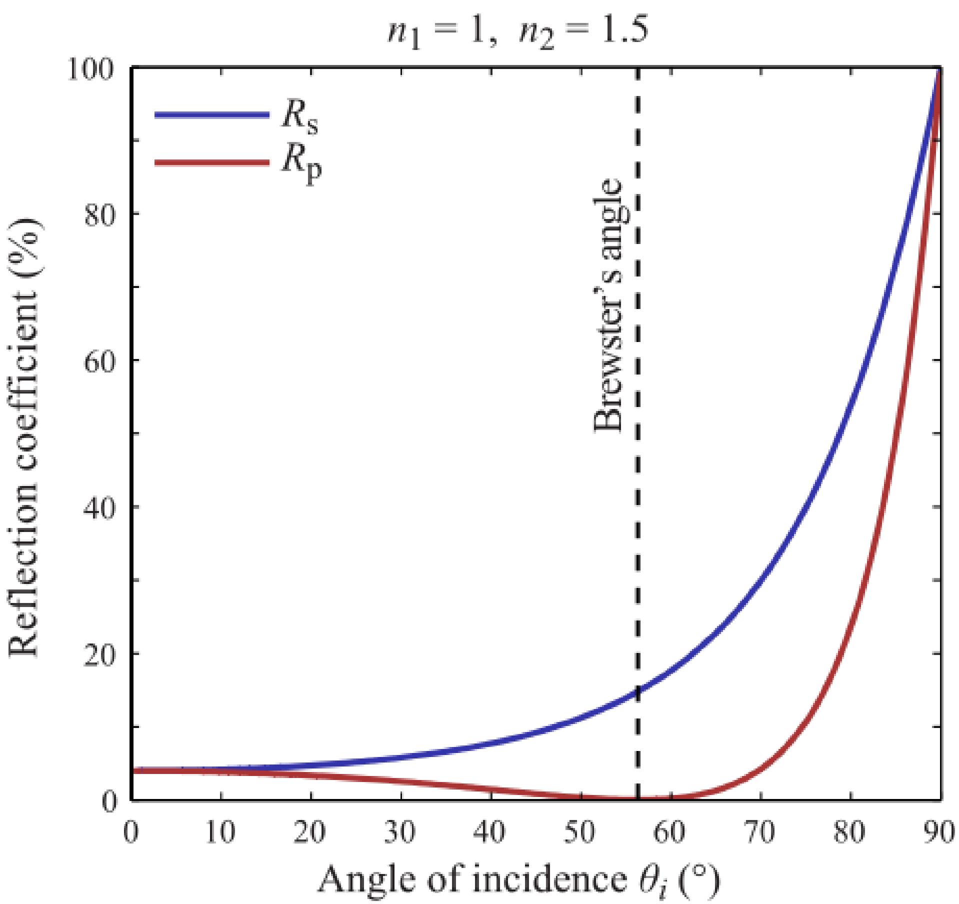
$$R_{\mathrm{p}} = \left| \frac{n_1 \cos\theta_{\mathrm{t}} - n_2 \cos\theta_{\mathrm{i}}}{n_1 \cos\theta_{\mathrm{t}} + n_2 \cos\theta_{\mathrm{i}}} \right|^2 = \left| \frac{n_1 \sqrt{1 - \left(\frac{n_1}{n_2} \sin\theta_{\mathrm{i}}\right)^2} - n_2 \cos\theta_{\mathrm{i}}}{n_1 \sqrt{1 - \left(\frac{n_1}{n_2}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

http://en.wikipedia.org/wiki/Fresnel_equations

Special Cases of Reflection

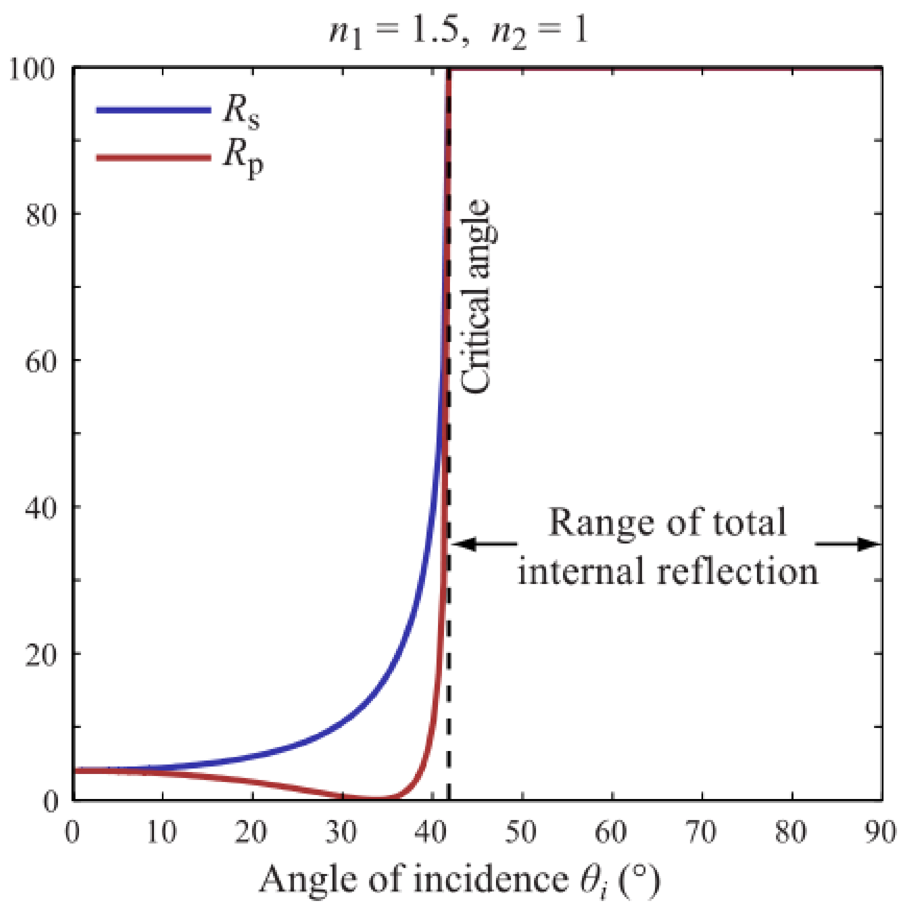
Polarized Reflection

$$\theta_B = \tan^{-1}\left(\frac{n_2}{n_1}\right)$$



Total Internal Reflection

$$\theta_i = \theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$$

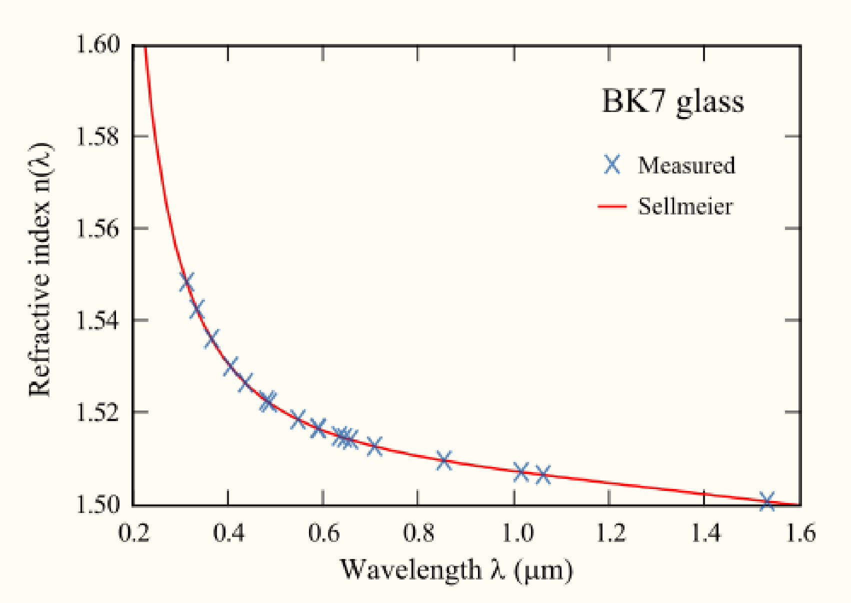


http://en.wikipedia.org/wiki/Fresnel_equations

Fresnel Coefficients

$$R_s = \left|\frac{n_1\cos\theta_i - n_2\cos\theta_t}{n_1\cos\theta_i + n_2\cos\theta_t}\right|^2 = \left|\frac{n_1\cos\theta_i - n_2\sqrt{1-\left(\frac{n_1}{n_2}\sin\theta_i\right)^2}}{n_1\cos\theta_i + n_2\sqrt{1-\left(\frac{n_1}{n_2}\sin\theta_i\right)^2}}\right|^2$$

$$R_p = \left|\frac{n_1\cos\theta_t - n_2\cos\theta_i}{n_1\cos\theta_t + n_2\cos\theta_i}\right|^2 = \left|\frac{n_1\sqrt{1-\left(\frac{n_1}{n_2}\sin\theta_i\right)^2} - n_2\cos\theta_i}{n_1\sqrt{1-\left(\frac{n_1}{n_2}\sin\theta_i\right)^2} + n_2\cos\theta_i}\right|^2$$



Look at dispersion: for our wavelength range, n varies from 1.55 to 1.50. At normal incidence:

$$R = \left|\frac{n_1 - n_2}{n_1 + n_2}\right|^2$$

For n_1 = 1.0 and n_2 = 1.55, R = 0.046.

For n_1 = 1.0 and n_2 = 1.50, R = 0.040.

R does not vary rapidly around normal incidence (θ_i = 0); therefore, we can expect that R varies only slightly and is ~4.0% *per air/glass interface*. How many interfaces do we have for the blank glass slide?

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.

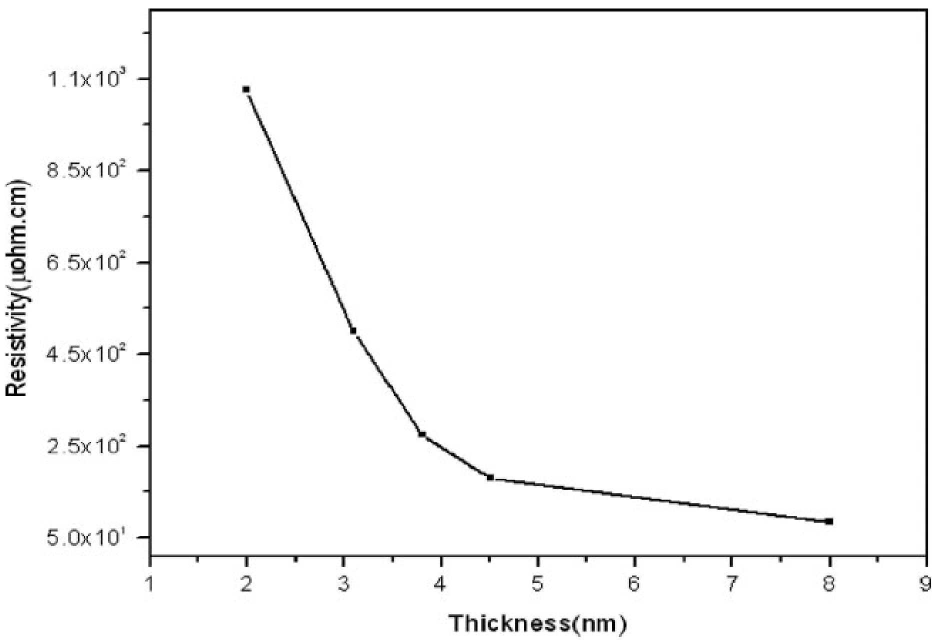
http://www.cytodiagnostics.com

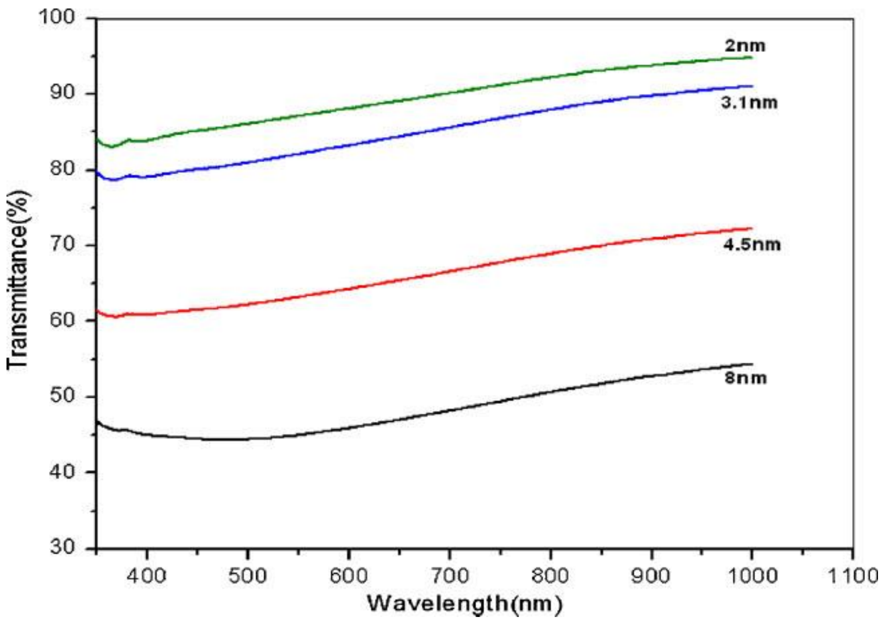
Ultrathin chromium transparent metal contacts by pulsed dc magnetron sputtering

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

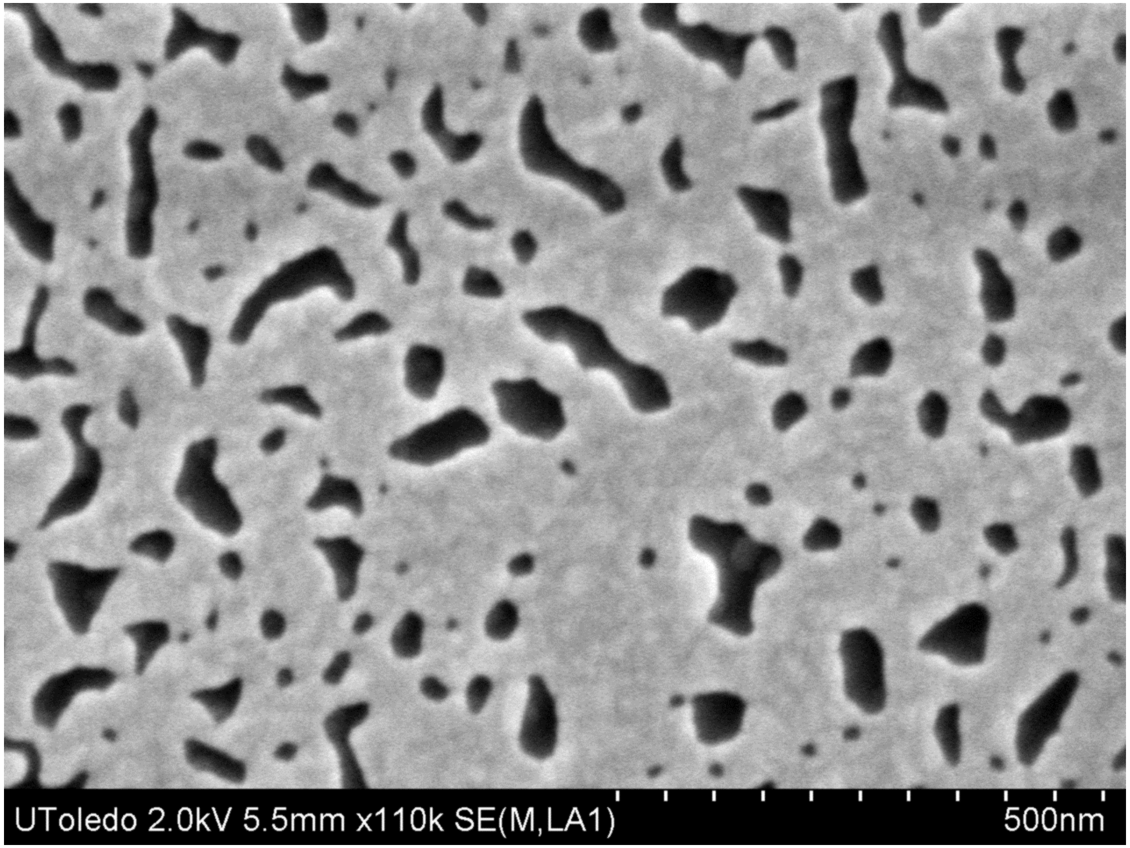




"The sheet resistance values corresponding to the 2, 3.1, 4.5 and 8 nm thick films are 5×10^3, 1.6×10^3, 4×10^2 and 1×10^2 Ω/□, respectively."

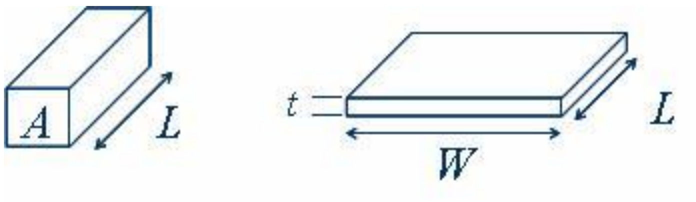
Phys. Status Solidi A **207**, No. 7, 1586–1589 (2010) / **DOI** 10.1002/pssa.200983732

Sheet Resistance – importance of film morphology



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

Sheet Resistance



Regular 3-D conductor, resistance *R* is:

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

where ρ is the resistivity (Ω·m), *A* is the cross-section area, and *L* is the length. For *A* in terms of *W* and *t*,

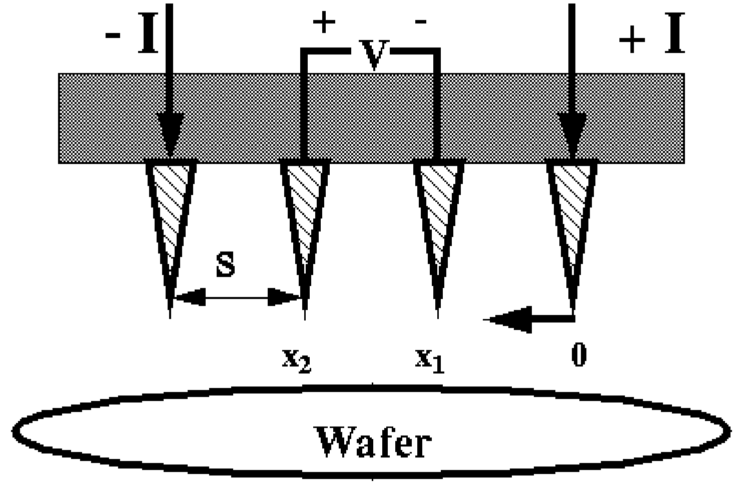
$$R = \frac{\rho}{t}\frac{L}{W} = R_s \frac{L}{W}$$

where R_s is the Sheet Resistance. Units are ohms, but can also express this as "ohms per square", or Ω/□, or Ω/sq.

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

http://en.wikipedia.org/wiki/Sheet_resistance

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: $$\Delta R = \rho\left(\frac{dx}{A}\right)$$

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:

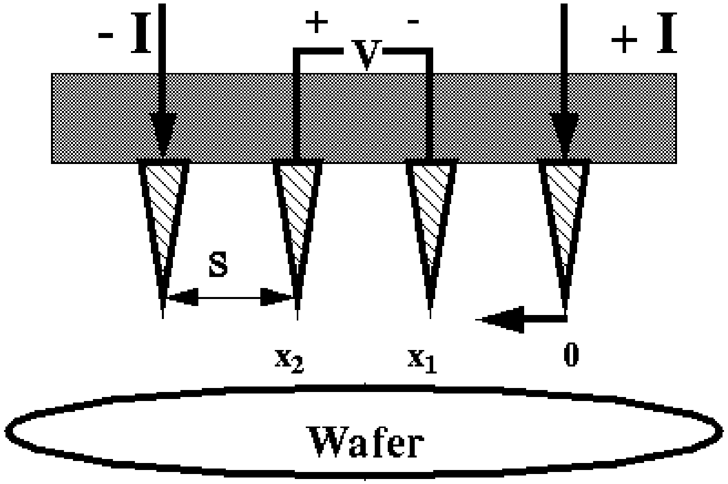
$$R = \int_{x_1}^{x_2} \rho \frac{dx}{2\pi x^2} = \frac{\rho}{2\pi}\left(-\frac{1}{x}\right)\Bigg|_{x_1}^{x_2} = \frac{1}{2s}\frac{\rho}{2\pi}$$

Superposition of current at outer two tips leads to R = V/2I, so that

$V/2I = \rho\,/(4s\pi) \rightarrow \rho = 2\pi s(V/I)$

http://www.fourpointprobes.com/four-point_probe.html

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.

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

As before, superposition of current at outer two tips leads to R = V/2I, so that the 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 Resistance*** is defined as:

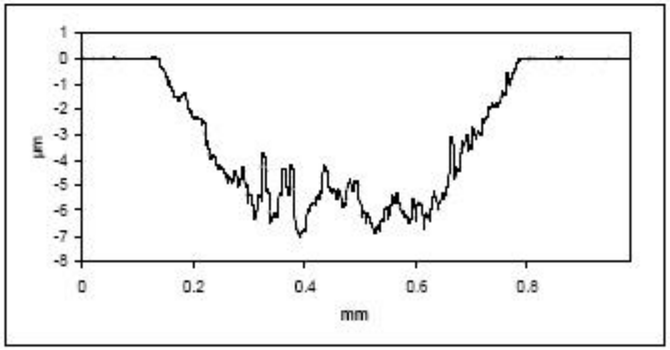
$$R_s = \frac{\rho}{t} = k\left(\frac{V}{I}\right)$$

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

http://www.fourpointprobes.com/four-point_probe.html

Contact (Stylus) Profilometry

Contact profilometer. A diamond stylus moves vertically into contact with a sample and then moves laterally across the sample for a specified distance and specified contact force. A profilometer measures small surface variations in vertical stylus displacement as a function of position. A typical profilometer can measure small vertical features ranging in height from 10 nm to 1 mm. The height position of the diamond stylus generates an analog signal which is converted into a digital signal stored, analyzed and displayed.



Advantages of contact profilometers:

- Acceptance: Most surface finish standards based on contact profilometers;
- Surface Independence: Surface contacting often an advantage in dirty environments (non-contact methods may measure surface contaminants);
- Resolution: Stylus tip radius can be as small as 20 nm, significantly better than white-light optical profiling. Vertical resolution is typically sub-nanometer as well.

From http://en.wikipedia.org/wiki/Profilometer