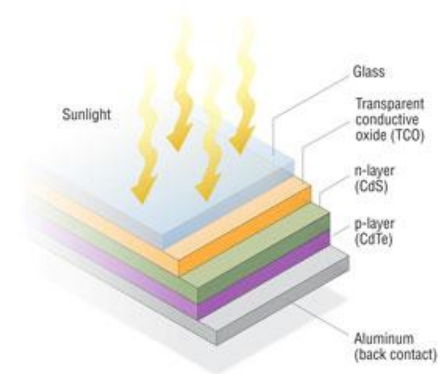
Laboratory #3 Guide: Optical and Electrical Properties of Transparent Conductors -- September 23, 2014

Introduction

Following our previous lab exercises, you now have the skills and understanding to control and characterize the light source – a tungsten-halogen lamp coupled to a diffraction grating monochromator. This light source provides a tunable source of light extending from ~350 nm to 1500 nm (1500 nm = 1.5 μm). In this lab, you will utilize this light source to measure the optical properties of samples known generally as transparent conductors.

Typical solar cells consist of a "sandwich" of material layers, with two important contact layers (one in the front, and one in the back) consisting of highly-conducting materials (see figure for one example). Examples of metallic conducting films used in either experimental or commercial solar cells include Al, Mo, Au, Ag, and Cr. In order to achieve the best possible electrical conductivity (and reduce the voltage losses associated with resistance), metallic films are typically used at large thicknesses that result in total opacity. In other words, light cannot pass through the films, and they act essentially as mirrors. Opaque conducting films may be used as the **back contact** to the solar cell.



Note that the diagram shows the sunlight passing through glass, and then through a TCO (transparent conducting oxide) **front contact** layer before most of the sunlight is absorbed within the semiconducting layers, i.e. the CdS and CdTe. Although some types of solar cells use an electrically conducting grid to provide the combination of *conductivity* (through the metallic grid) and *transparency* (through the openings in the grid), many types of solar cells use transparent conductors instead of a grid, or combine a transparent conductor with a grid. The transparent conducting layer must achieve two properties simultaneously: (**1**) good electrical conductivity, and (**2**) good transparency to light.

Only specific types of materials can be used as good transparent conductors. Examples include metal oxides which are "doped" to render them electrically conductive, or very thin films of metals which are conductive yet so thin as to be partially transparent. As you will find, every transparent conducting material presents a trade-off between conductivity (which should be high for the best solar cell electrical performance) and transparency (which should be high to maximize the amount of light transmitted through to the semiconductor layers where the electrons and holes are separated to generate electrical current).

In this set of lab exercises, we will explore the properties of optical transmission (Week #1) and electrical conductivity (Week #2) for a variety of samples, including thin metallic films, a simple TCO film of indium tin oxide (ITO), and two different commercial coated-glass substrates (TEC-8 and TEC-15). In addition to optical and electrical property measurements, we will also learn in Week #2 how to use the Dektak Profilometer (to be used only with supervision from a trained user) to measure the thickness of a thin film. After the series of optical and electrical measurements, and the determination of the thickness of one chromium (Cr) semi-transparent metallic film, you will have assembled all the data necessary to provide insights into how transparency and conductivity are interdependent.

Goals of Lab #3: Optical and Electrical Properties of Transparent Conducting Thin Films

Your 7 samples will consist of a bare glass slide (1" x 3"), three different Cr film thicknesses on glass slides, a sample of TEC-8 coated glass substrate, a sample of TEC-15 coated glass substrate, and an ITO-coated glass substrate.

For each sample, you will measure (**1**) the transmission (T) spectrum from 350 to 1500 nm; (**2**) the reflection (R) spectrum from 350 nm to 1500 nm, and the electrical sheet resistance. Use the results of the transmission and reflectance spectra to calculate the absorption (A) spectrum for each sample. Your T and R measurements will be made at close to normal incidence, so that the light beam incident on the sample forms a 90° angle with the surface of the sample.

In the 2^{nd} Week of the lab, you will use the Four Point Probe to measure the sheet resistance of each of these 7 samples.

Also in Week #2, you will use the Dektak Profilometer to measure the film thickness of the thickest (most conductive) Cr film.

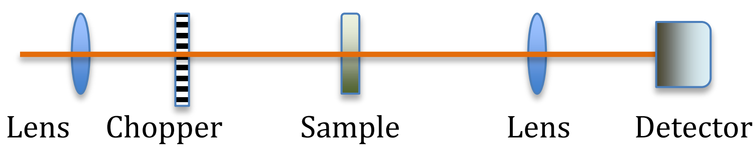
Concepts

Solar modules consist of solar cells connected electrically to create a final photovoltaic product (a "module"). When illuminated by sunshine, the solar cells that make up the solar module convert sunlight to electricity. We know that terrestrial sunlight includes the broad range of wavelengths (or frequencies, which determine the "color" on the light as well as the photon energy) from the ultraviolet (~300 nm) to the mid-infrared wavelengths (e.g., 4000 nm, or 4 μm). However, solar cells can efficiently convert only certain wavelengths of light to electrical power. As we consider how solar cells respond to different wavelengths of light, we'll first investigate how transparent conducting films transmit, reflect and absorb light of different wavelengths.

The fundamental optical properties of a sample can be described as the wavelength-dependence of the transmission, reflection, and absorption of light. Since energy is conserved when light is incident on a sample and partially transmitted, reflected, and/or absorbed, we can refer to the relationship T + R + A = 1, where the values of T, R, and A are measured as the fraction of incident light that is either Transmitted, Reflected, or Absorbed. Light that is absorbed by the "front" layers such as the glass and/or the transparent conducting layer is not converted to electrical energy but rather generates heat (thermal energy). In this way, only the transmitted light can produce electrical power. Determining whether light that is *not* transmitted is reflected or absorbed is important so that appropriate steps can be taken in a final product (e.g., including an antireflection coating to minimize the reflected light).

The electrical conductivity of a thin film is characterized by the *sheet resistance*, which tells you how much resistance will be encountered by a DC current flowing within the film. Recall that V = IR where the voltage (V) drops across a resistance (R) when a current (I) flows through it. This voltage drop would reduce the useful voltage of a solar cell available to be used for powering the "load" (the electrical appliances being powered by the solar cell or a solar module).

There are multiple ways to measure the thickness of a thin film of material on a glass substrate. In this case, we will use a mechanical technique based on "stylus profilometry". A profilometer uses a stylus to measure the profile of a surface, including aspect such as the surface roughness and, when presented with a "cliff" or "step" between a substrate and the film, the thickness of the film.



Example setup for transmission measurement

Experimental Steps

1. Confirm that your light measurement system (light source, CM 110, alignment lenses, chopper, thermopile detector, together with the 1010 amplifier, SR510 LIA, and USB DAQ device) is working well, with low noise. You can do so by visually confirming the alignment, obtaining and optimizing a signal derived from a single wavelength, and then switching over to the smallest slit size to confirm that you can measure the signal at very low intensities. Ensure that you have adequate space in your setup for the samples to be inserted.

2. Measure the transmission spectrum $T(\lambda)$ for your set of samples. Think through how this will be done: since $T(\lambda) = Sig_{trans}(\lambda)/Sig_{inc}(\lambda)$, you must measure both the incident spectrum (i.e., $Sig_{inc}(\lambda)$, measured with no sample in the path), and then measure the spectrum reaching the detector *with* the sample in the optical path (i.e., $Sig_{trans}(\lambda)$). Note that $Sig_{inc}(\lambda)$ is essentially a

reference spectrum, and that you are performing a typical measurement done in a commercial spectrophotometer. Insertion of a sample may change the phase of the signal measured by the LIA vs. the chopper reference, so careful adjustment of the phase setting on the LIA will be required. Also, check on the possibility that the incident light spectrum has changed between the beginning (incident spectrum measurement) and the end of your spectral measurements: re-measure the incident light spectrum after you have measured with each of the 7 samples inserted in the beam path. Finally, be aware that if you change the Sensitivity setting on the SR510, the same light intensity will produce a different Output voltage! This may become more important for later measurements ($R(\lambda)$).

3. To accomplish measurement of $R(\lambda)$ for each sample, set up a reflectance measurement using the glass slide as the sample using the smallest practical deviation from 90° angle of incidence (θ_{inc}) . We're relying on the fact that for relatively small deviations from normal incidence, the reflectance does not vary considerably.

   The reflectance measurement takes some thought, and you'll need to be very careful on this part of the lab in order to measure high quality data. In order to measure the amount of light lost to reflection, one must measure the *reflected* light. We do not have a 100% reflective mirror to use as a reference for this measurement. We do, however, have a very good *standard* to use for a reference measurement since the blank glass slide has a well-known refractive index of ~1.5. Refer to the Wikipedia entry for Fresnel Equations to calculate the reflection coefficient R as the average of R_s and R_p using your specific angle of incidence (recall that the s and p subscripts refer to the s-wave and the p-wave). Since we're assuming our light beam is unpolarized, we'll use the average of the two. Recall that $\theta_i = \theta_r$. Your anser may be remarkably close to the normal incidence reflectance, which does not depend upon polarization and is given by $R = [(n_1 - n_2)/(n_1 + n_2)]^2$. For $n_1 = 1.0$ (air) and $n_2 = 1.5$ (glass), the reflectance is equal to 0.04 (or, 4%). Note however that a glass slide will reflect from both air-glass interfaces. So expect a value close to ~8%.

4. Next, notice that $A = 1 - T - R$, and that since you have the spectral values for T and R, you can calculate $A(\lambda)$ for each sample. Take note of where absorption does and does not occur within the measured spectra. What if you measure a negative value for A at some wavelengths? Is $A < 0$ physically possible for these specific samples under these conditions?

5. Measure the sheet resistance for each of the seven samples. When you make these measurements, make sure that you have a qualified user assist with the process and measurements (this will be done in Week #2 of this lab). Note how many measurements you make on each sample (make several), and use

these values to calculate a mean as well as the standard deviation. Include these (mean and SD) values in a table in your report.

Your Laboratory Report

- *Make thoughtful graphs of your T, R, and A spectra, choosing how to present the data. Keep in mind that you've measured three Cr samples, two TEC glass samples, and a sample of ITO. It would be good to be able to compare the three Cr samples to one another. It may also be good to compare A for one of each type of sample. However you choose to display the spectra, describe what you note as the interesting features for each graph, and for each type of sample.*

- *Use the four point probe to measure and report on the sheet resistance values for each of the seven (six without the blank glass, but measure the sheet resistance of it also) 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.*

- *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?*

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

- *Of the 7 films you have examined, which would function best as the top contact of a solar cell, and why?*