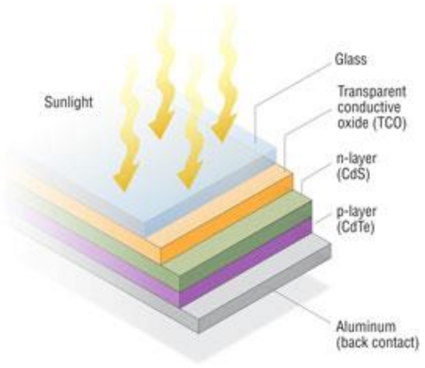
Laboratory #4 Guide: Optical Determination of Absorption Coefficient and Band Gap Energy of CdS, CdTe, and c-Si – October 21, 2014

Introduction

You now have constructed a computer-controlled light source and detection system, and have employed this measurement system to measure the optical properties of samples. Your measurements enabled the determination of the samples' absorption spectra from measurements of transmission and reflectance. In this lab, you will utilize this light source to measure the optical properties of semiconductor samples used in CdS/CdTe thin film solar cells, and of c-Si used as the absorber in majority of the solar cells manufactured for terrestrial photovoltaic application. Space, or "extra-terrestrial", PV applications -- such as for satellites -- typically use high efficiency epitaxial III-V solar cells based on GaAs and related single-crystal materials – resulting in a high ratio of power to weight (specific power).



Previously, you measured the properties of transparent conductors. In this lab, you will measure the properties of the semiconductor layers designed to absorb the sunlight. In the figure at right, note that both CdS and CdTe layers are used. You'll find that one of these layers in particular absorbs the majority of the sunlight transmitted by the TCO.

Within these semiconductor layers, light absorption depends strongly on the wavelength of the light and also on the layer thickness. Specifically, the intensity of light propagating within a material decreases depending on the absorption coefficient α, the film thickness t, and the wavelength of light as follows:

$I(\lambda, \alpha, t) = I_0(\lambda) \exp(-\alpha(\lambda)t)$; note that $\alpha = \alpha(\lambda)$ is a *function of wavelength*, as is the incident intensity. In this equation, $I_0(\lambda)$ represents the incident light spectrum, ignoring reflection losses. Additional notes on the determination of $\alpha(\lambda)$ follow below.

Goals of Lab #4

Your 4 samples consist of a CdTe sample on glass, a CdS sample on glass, and two different c-Si wafers. The CdTe and CdS samples were grown on TEC-15 coated glass at UT's PVIC by using RF magnetron sputtering, and the c-Si wafers are monocrystalline samples prepared with doping densities which differ from one another. The sample thicknesses are summarized in the table below.

Sample	**Thickness (cm)**
CdS	50×10^{-7}
CdTe	950×10^{-7}
Si Sample 1	$300 +/- 25 \times 10^{-4}$
Si Sample 2	$500 +/- 25 \times 10^{-4}$

For each sample, you will measure (**1**) the transmission (T) spectrum from 350 to 1500 nm and (**2**) the reflection (R) spectrum from 350 nm to 1500 nm. Use the results of the transmission and reflectance spectra to calculate the absorption (A) spectrum for each sample, expressed as the fraction (0 to 1) of incident light that is absorbed. Your T and R measurements will be made at *close to normal incidence*, so that the light beam incident on the sample forms nearly a 90° angle with the surface of the sample.

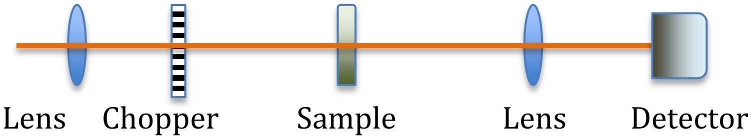
For the lab report:

1) Present and describe your transmission, reflectance, and absorption data for each sample (one graph for each sample)
2) Use the measured optical absorption, along with the sample thickness values, to calculate the wavelength-dependent absorption coefficients $\alpha(\lambda)$ for each of the four samples. Make two graphs of the absorption coefficient data – (**a**) one showing the CdS and CdTe absorption coefficients, and (**b**) the other samples.
3) *Analyze the absorption coefficient data for each sample* to determine the type of bandgap (direct, or indirect). Plot the results: show your fit to the data, and show the deduced bandgap energy.

Concepts

We focused previously on the fact that only light transmitted through the transparent conducting layer *potentially* contributes to a solar cell's production of electricity. Similarly, only light absorbed by the semiconductor layer(s) can *potentially* contribute to the photocurrent (the current resulting directly from generation of electrons and holes by photon absorption). Light that is transmitted through the semiconductor layer(s) – i.e., light that is not absorbed – cannot be converted to electrical energy. Note also that while each photon absorbed within the semiconductor layer generates an electron-hole pair, some of these charge carriers do not survive to be collected as photocurrent. Instead, some of the electrons and holes recombine, one electron with one hole, generating either a photon or thermal (heat) energy. Recombination represents the principal mechanism by which the current density in a solar cell is reduced below the current that would be reached if each photo-generated electron-hole pair contributed an electron to the cell's current.

Therefore, the wavelength-dependent absorption coefficient of the semiconductor, together with the film or wafer thickness, determines how much of the incident light is actually absorbed (at each wavelength). Photons with energy below the band gap energy are not absorbed and therefore do not generate an electron-hole pair (nor do they contribute to the photocurrent or to the electrical energy generation).



Example setup for transmission measurement

Consider how you can calculate $\alpha(\lambda)$ from your measured values. Since Beer's Law refers to the attenuation of light *within the absorbing layer*: $I(x) = I_0\exp(-\alpha x)$, where I_0 refers to the light intensity just *inside* the sample – i.e., the incident intensity *in the case where the reflection is negligible*. Our samples reflect some fraction of the incident light, so you need to be careful about how you define I_0. If you have measured $R(\lambda)$, then $I_0(\alpha)$ just inside the sample will be the incident intensity minus $R(\lambda)$. Following a careful handling of the problem at hand, one finds that:

$$e^{-\alpha(\lambda)d} = \frac{T}{1-R} \Rightarrow \alpha(\lambda)d = -\ln\left(\frac{T}{1-R}\right)$$

, where T is transmitted light, and 1-R is the intensity of light just inside the sample.

Experimental Steps (Include these items within your lab report)

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 a small slit size to confirm that you can measure a good quality signal at very low intensity. Ensure that you have adequate space in your setup for the samples to be inserted.

2. Measure the transmission spectra $T(\lambda)$ for each of the samples. As before, be aware that the Sensitivity setting on the SR510 influences the Output voltage. Note the parameters for your measurement (SR510 sensitivity setting, whether the Dexter amplifier is being used). This information is often essential in figuring out the final values for $T(\lambda)$ and/or $R(\lambda)$.

3. To accomplish measurement of $R(\lambda)$ for each sample, set up a reflectance measurement using the glass slide as a reference sample using the smallest

practical deviation from 90° angle of incidence (θ_{inc}) . Again, rely on the fact that for relatively small deviations from normal incidence, the reflectance does not vary significantly. As before, a glass slide will reflect from both air-glass interfaces resulting in a signal correlated with an ~8% reflectance (R = 0.08).

4. Calculate $A(\lambda)$ (a value between 0 and 1) and $\alpha(\lambda)$ (units of cm^{-1}) for each sample. Discuss the results, including identifying the spectral regions where light is most strongly absorbed, and where the sample shows high transparency.
5. Use your data to determine the bandgap type (direct, or indirect?), and the bandgap energy (E_g, in eV). Compare your results (type, and E_g in eV) with evidence you find in the literature or another reputabe source