Bandgap measurements of nonspecular materials using a bifurcated fiber optic method of diffuse reflectance

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Abstract

A method for determining bandgap energy using diffuse reflection is presented. The method uses bifurcated fiber optic cables to measure the diffuse reflection of diffusely reflective materials. The absorption spectrum is extrapolated from the diffuse reflection spectrum and used to determine the bandgap of powdered materials. The theory of nonspecular reflection, the Kubelka-Munk model, and bandgap structure is explored. The methods, procedure, and equipment involved in measurements are detailed. The bandgap energies of titanium dioxide, tin sulfide, and 10 percent tin doped indium oxide are determined. The measured bandgap energy of TiO$_2$ agrees within 0.03 eV of the accepted value. The measured bandgap energy of SnS was inconsistent with the accepted value and is most likely attributable to incorrect infrared spectral data. The measured bandgap energy of In$_{2-x}$Sn$_x$O$_3$ agrees within 0.1 eV of the accepted value.
# Table of Contents

Chapter 1 – Introduction.................................................................................................................. 4  
1.1 Motivation and Objective........................................................................................................... 4  
1.2 Nonspecular Reflection............................................................................................................. 5  
1.3 Kubelka-Munk Theory .............................................................................................................. 5  
1.4 Bandgap of a Material ............................................................................................................. 8  

Chapter 2 – Methods ...................................................................................................................... 10  
2.1 Equipment and System Preparation ......................................................................................... 10  
2.1.1 Spectrometers .................................................................................................................... 10  
2.1.2 Bifurcated Fiber Optic Cables ............................................................................................ 12  
2.1.3 Light Sources ..................................................................................................................... 12  
2.1.4 Sample and Experiment Apparatus ..................................................................................... 13  
2.1.5 LabVIEW ........................................................................................................................... 13  
2.2 Powder Characterization ......................................................................................................... 14  
2.2.1 Spectrum Measurements...................................................................................................... 14  
2.2.2 Measurement of Bandgap Energy ....................................................................................... 14  

Chapter 3 – Results ....................................................................................................................... 15  
3.1 Raw Diffuse Reflection............................................................................................................. 15  
3.2 Reflectivity Measurements...................................................................................................... 17  
3.3 Bandgap Measurements........................................................................................................... 21  

Chapter 4 – Discussion.................................................................................................................... 23  

Chapter 5 – Conclusion................................................................................................................... 23  

Chapter 6 – References.................................................................................................................. 24  

Chapter 7 – Appendix I................................................................................................................. 26
## List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1.1: Bifurcated optic cable. A) Optic cable for light source input B) Optic cable for spectrometer analysis C) Bifurcated cable to supply source light and gather reflected light.</td>
<td>4</td>
</tr>
<tr>
<td>Figure 1.2: Light flux inside a diffusely reflective material</td>
<td>6</td>
</tr>
<tr>
<td>Figure 1.3: Direct and indirect electron transitions</td>
<td>9</td>
</tr>
<tr>
<td>Figure 2.1: The internal components of the Ocean Optics HR-4000 spectrometer. 1) SMA connector 2) Slit 3) Filter 4) Collimating Mirror 5) Grating 6) Focusing Mirror 7) L2 Detector Collection Lens 8) CCD Array</td>
<td>11</td>
</tr>
<tr>
<td>Figure 2.2: The internal components of the Ocean Optics NIR 256-2.5 spectrometer. 1) SMA Connector 2) Slit 3) Filter 4) Collimating Mirror 5) Grating 6) Focusing Mirror 7) InGaAs Detector</td>
<td>12</td>
</tr>
<tr>
<td>Figure 2.3: Ocean Optics diffuse reflection set up. 1) Bifurcated optic fiber 2) Ceramic sample disc 3) Sample material 4) Angular alignment apparatus</td>
<td>13</td>
</tr>
<tr>
<td>Figure 3.1: Background spectrum intensity, reflection standard intensity, and raw reflection of titanium dioxide</td>
<td>15</td>
</tr>
<tr>
<td>Figure 3.2: Background spectrum intensity, reflection standard intensity, and raw reflection of tin sulfide</td>
<td>16</td>
</tr>
<tr>
<td>Figure 3.3: Background spectrum intensity, reflection standard intensity, and raw reflection of indium tin oxide</td>
<td>16</td>
</tr>
<tr>
<td>Figure 3.4: Diffuse reflectivity vs wavelength of TiO$_2$ powder</td>
<td>17</td>
</tr>
<tr>
<td>Figure 3.5: Diffuse reflectivity vs energy of TiO$_2$ powder</td>
<td>18</td>
</tr>
<tr>
<td>Figure 3.6: Diffuse reflectivity vs wavelength of SnS Powder</td>
<td>18</td>
</tr>
<tr>
<td>Figure 3.7: Diffuse reflectivity vs energy of SnS Powder</td>
<td>19</td>
</tr>
<tr>
<td>Figure 3.8: Diffuse reflectivity vs wavelength of In$_{2-x}$Sn$_x$O$_3$ powder</td>
<td>19</td>
</tr>
<tr>
<td>Figure 3.9: Diffuse reflectivity vs energy of In$_{2-x}$Sn$_x$O$_3$ powder</td>
<td>20</td>
</tr>
<tr>
<td>Figure 3.10: Direct bandgap measurement of TiO$_2$</td>
<td>21</td>
</tr>
<tr>
<td>Figure 3.11: Indirect bandgap measurement of SnS</td>
<td>22</td>
</tr>
<tr>
<td>Figure 3.12: Direct bandgap measurement of In$_{2-x}$Sn$_x$O$_3$</td>
<td>22</td>
</tr>
</tbody>
</table>
Chapter 1 – Introduction

1.1 Motivation and Objective

A semiconductor is a chemical element or compound that is able to conduct electricity under certain conditions but not others, having an electrical conductivity between a conductor and an insulator. Semiconductors have discrete energy gaps that allow them to be uniquely utilized in a wide array of applications. Research in semiconductors regularly applies the method of optical spectroscopy on thin films and powders. This method yields critical information pertaining to the chemical structure, vibronic and electronic relaxations and excitations, and optical constants such as the absorption coefficient and refractive index. Diffuse Reflectance Spectroscopy, or Elastic Scattering Spectroscopy, is a technique that measures the characteristic reflectance spectrum produced as light reflects through a medium. The diffuse reflection is produced by a sample’s rough surfaces reflecting light in all directions. The light collected contains many characteristics of the analyzed material, such as refractive index, reflectivity, and absorption. Integrating spheres are often used to capture all the light needed to extrapolate these characteristics. Integrating spheres are expensive and take time consuming measurements. An alternative and simpler method is to use bifurcated optical cables in diffuse reflectance spectroscopy. Figure 1.1 depicts a bifurcated fiber optic cable where light is sent from the source to the sample and a fraction of the reflected light travels to the spectrometer for analysis.

Figure 1.1: Bifurcated optic cable. A) Optic cable for light source input B) Optic cable for spectrometer analysis C) Bifurcated cable to supply source light and gather reflected light.
The use of fiber optic cables provides a highly flexible, inexpensive, and robust method to deliver and receive light. The cables are used in a wide variety of spectroscopic techniques due to this adaptability.

1.2 Reflection

The bandgap of a semiconductor is most commonly determined by optical measurements. The reflection of light off a material has sufficient information to calculate the bandgap. Reflection is defined as a ratio of the reflected light's intensity to the incident light's intensity.

\[ R_{\text{Sample}}(\lambda) = R_{\text{Reference}}(\lambda) \frac{S_{\text{Sample}}(\lambda) - S_{\text{Background}}(\lambda)}{S_{\text{Reference}}(\lambda) - S_{\text{Background}}(\lambda)} \]  \hspace{1cm} (1.1)

Here \( R_{\text{Sample}}(\lambda) \) is the reflectivity of the material, bound between 0 and 1. \( S_{\text{Sample}}(\lambda) \) is the intensity that has been diffusely reflected by the sample. \( S_{\text{Reference}}(\lambda) \) is the intensity that has been reflected by a reference material which has a high reflection coefficient. \( S_{\text{Background}}(\lambda) \) is the intensity measured when the reflected light is deflected away from the bifurcated cable. The background intensity is subtracted from both the sample and reference intensity. The sample reflectance is also multiplied by the reference reflectance to give the accurate value for absolute reflection.

1.3 Kubelka-Munk Theory

The laws of reflection are always observed regardless of surface orientation. However, diffuse reflection is not calculated the same as specular reflection. Light reflects diffusely off rough surfaces in many different directions. Diffusely reflected light is modeled by the Kubelka-Munk method, which allows the calculation of reflectance from a layer that both scatters and absorbs light. This models the light as a flux rather than a plane wave, and focuses on the upward and downward flux through a small portion, \( dz \), within the sample. The two flux model means that only diffuse light is considered. The upward flux and downward flux are denoted \( f(z) \) and \( l(z) \) respectively, as shown in Figure 1.2.
Figure 1.2: Light flux inside a diffusely reflective material

The scalar equation of transport with azimuthal symmetry and planar geometries is shown in equation 1.2, where \( u = \cos(\theta) \). The absorption coefficient is denoted as \( k \) and the scattering coefficient is denoted as \( s \). Both coefficients have units of inverse length. Equation 1.2 models isotropic scattering and monoenergetic radiation. Isotropic scattered light is scattered with equal efficiency in all possible directions. Monoenergetic radiation consists of photons with energies confined to an exceptionally narrow range.

\[
u \frac{\partial \Phi(z, u)}{\partial z} = -(k + s)\Phi(z, u) + \frac{s}{2} \int_{-1}^{1} \Phi(z, u')du'
\]  

(1.2)

The distribution function is shown in equation 1.3, where \( \Theta \) is the Heaviside step function.

\[
\Phi(z, u) = \Theta(-u)I(z) + \Theta(u)J(z)
\]

(1.3)

Applying the distribution function to equation 1.2 gives the infinitesimal change in \( I(z) \) and \( J(z) \) shown in equations 1.4 and 1.5.

\[
\frac{dJ(z)}{dz} = -(k + s)J(z) + s(I(z))
\]

(1.4)

\[
\frac{dI(z)}{dz} = (k + s)I(z) - s(J(z))
\]

(1.5)
Equations 1.4 and 1.5 are combined as the ratio,

$$r(z) = \frac{J(z)}{I(z)}$$

to provide the expression in equation 1.6,

$$\frac{1}{s} \frac{dr(z)}{dz} = r(z)^2 - 2(2a - 1)r(z) + 1$$  \quad (1.6)$$

where

$$a = \frac{k + s}{s}.$$  

The ratio $r(z)$ does not change if the observer is outside of the material, nor is it of consequence where the observer is located in space as long as the observer is outside of the material. Solving equation 1.6 for $a$ with this realization gives

$$a = \frac{(1 + R_\infty)^2}{4R_\infty}$$  \quad (1.7)$$

where $R_\infty$ is the absolute diffuse reflectance, given as

$$R_\infty = r(\infty) = 1 + \frac{k}{s} - \sqrt{\frac{k}{s} \left( 2 + \frac{k}{s} \right)}$$  \quad (1.8)$$

This models the material as an infinitely thick and opaque layer, but for practical purposes with fine powder it is achieved at a layer depth of a just a few millimeters. The K-M Function, $f(R_\infty)$, is used for comparison to quantitative experimental analysis.

$$f(R_\infty) = \frac{(1 - R_\infty)^2}{4R_\infty} = \frac{k}{s}$$  \quad (1.9)$$

where $k$ is the effective absorption coefficient and $s$ is the effective scattering coefficient of the sample. The scattering coefficient is assumed to be constant over the wavelength region measured and is thusly a scaling factor. The K-M function then is directly proportional to the absorption coefficient $\alpha$ seen in equation 1.12.
1.4 Bandgap of a Material

The bandgap is the range of energy between the bottom of the conduction band and top of the valence band in a semiconductor or insulator; an energy range where no electron states exist. Each solid has a unique energy-band structure and provides varying electrical attributes. The relationship between complex permittivity, $\epsilon$, and the complex index of refraction, $N$, is needed to relate the diffuse reflection, and subsequently the absorption coefficient, to the bandgap energy.

$$\epsilon = N^2$$  \hspace{1cm} (1.10)

The complex index of refraction is given as,

$$N = n + i\kappa$$  \hspace{1cm} (1.11)

where $n$ is the real coefficient of the index of refraction, indicating the phase velocity, and $\kappa$ is the imaginary coefficient of the index of refraction, indicating the amount of attenuation loss while the electromagnetic wave propagates through a material.

Light passing through a medium has a portion that is always attenuated, and is defined in terms of $\kappa$ the imaginary coefficient of the index of refraction and $\lambda$, the wavelength. \(^5\)

$$\alpha = \frac{2\omega\kappa}{c} = \frac{4\pi\kappa}{\lambda}$$  \hspace{1cm} (1.12)

This absorption coefficient can be related to the imaginary coefficient of permittivity using equation 1.13.

$$\kappa = \frac{\alpha\lambda}{4\pi} = \frac{\epsilon_i}{2n}$$  \hspace{1cm} (1.13)

$$\frac{\alpha}{\hbar\omega} = C \frac{\epsilon_i}{n}$$  \hspace{1cm} (1.14)

Here $\hbar\omega$ is the energy of the photon and $C$ is a constant. The transition matrix element $P_{cv}$ and the joint density of states $D_j$ are used to provide an expression for the imaginary coefficient of permittivity. \(^5\)\(^7\)

$$D_j = \frac{1}{4\pi^3} \int \frac{dS_k}{|\nabla_k(E_c - E_v)|}$$  \hspace{1cm} (1.15)
\[ P_{cv} = \langle \psi_c | -e \vec{E} \cdot \hat{r} | \psi_v \rangle \]  
\[ \epsilon_i = C \frac{1}{\omega^2} |P_{cv}| D_j \] (1.16)

\[ \epsilon_i = C_2 \frac{1}{(\omega \hbar)^2} (\omega \hbar - E_{\text{bandgap}})^p \] (1.17)

An expression for the imaginary coefficient of the permittivity in terms of the bandgap energy is found by calculating the joint density of states.

\[ \epsilon_i = C_2 \frac{1}{(\omega \hbar)^2} (\omega \hbar - E_{\text{bandgap}})^p \] (1.18)

\[ \alpha \omega \hbar = C (\omega \hbar - E_{\text{bandgap}})^p \] (1.19)

The photon energy is depicted as \( \hbar \omega \) and the optical bandgap energy as \( E_{\text{bandgap}} \). C is a constant and \( p \) is the bandgap transition dependent exponent.

The bandgap transition exponent is dependent on whether the bandgap transition is direct or indirect, shown in figure 1.3, and if the transition is allowed or forbidden.

\[ \text{Indirect Transition, } p = 2 \quad \text{Direct Transition, } p = 0.5 \]

\[ \begin{align*} \text{Conduction Band} & \quad \text{Electron} \quad \text{Valence Band} \\ \text{Phonon} & \quad \text{Conduction Band} \quad \text{Valence Band} \end{align*} \]

\[ \text{Figure 1.3: Direct and indirect electron transitions.} \]

A direct bandgap transition is where the energy changes but the momentum is conserved. It is formed between the lowest energy point of a conduction band and the highest energy point of a valence band that have the same value in \( k \)-space. An indirect bandgap transition is one where both
the energy and the momentum change, and is formed between the lowest energy point of a conduction band and the highest energy point of a valance band that have differing locations in k-space. Transitions are allowed if the matrix element characterizing the transition is non-zero, whereas forbidden transitions have a matrix element equal to zero. The transitions and coefficients are derived through quantum perturbation theory of optical transitions.

\[
\text{Direct allowed: } p = \frac{1}{2} \\
\text{Direct forbidden: } p = \frac{3}{2} \\
\text{Indirect allowed: } p = 2 \\
\text{Indirect forbidden: } p = 3
\]

**Chapter 2 – Methods**

### 2.1 Equipment and System Preparation

Diffuse reflection of a sample is measured by shining broadband light on the powder material and collecting a portion of the light reflected.

#### 2.1.1 Spectrometers

There are two spectrometers used in these measurements. These spectrometers disperse all the light into its discrete wavelengths simultaneously. The Ocean Optics HR-4000 is used for the ultraviolet-visible portion of the spectrum, 200 nm to 1150 nm. It sends light onto a grating which separates the wavelengths onto a Toshiba TCD1304AP, a 3648-element charge-coupled device (CCD) array detector, enabling optical resolutions as precise as 0.27 nm. Figure 2.1 shows the internal components inside the Ocean Optics HR-4000 from the HR4000 and HR4000CG-UV NIR Series Spectrometers: Installation and Operation Manual.
The NIR 256-2.5 is used for the near infrared portion of the spectrum, 850 nm to 2600 nm. Light is also separated into discrete wavelengths onto a Hamamatsu G9208-256 InGaAs linear array enabling optical resolutions as precise as 6.85 nm. Figure 2.2 shows the internal components inside the Ocean Optics NIR 256-2.5 from the NIRQuest: Installation and Operation Manual.⁹
The internal components of the Ocean Optics NIR 256-2.5 spectrometer. 1) SMA Connector  2) Slit  3) Filter  4) Collimating Mirror  5) Grating  6) Focusing Mirror  7) InGaAs Detector

The component tables for each spectrometer are included in Appendix I.

2.1.2 Bifurcated Fiber Optic Cables

Two bifurcated fiber optic cables are used to transfer light to and from the sample. A general diagram of a bifurcated fiber optic cable is shown in Figure 1.1. The Ocean Optics ZFQ-9803 bifurcated optical fiber has a fiber diameter of 455 microns and is used for ultraviolet-visible measurements. The Ocean Optics QBIF400-VIS/NIR bifurcated optical fiber has a fiber diameter of 400 microns and is used for visible-near infrared measurements.

2.1.3 Light Sources

The Ocean Optics Mikropack DH-2000-Bal Deuterium Tungsten Halogen Light Source is used for the ultraviolet-visible measurements providing wavelengths of 215-400 nm (deuterium) and 360-2000 nm (tungsten halogen). The Ocean Optics Mikropack HL-2000 Tungsten Halogen Light Source is used for visible-near infrared measurements providing wavelengths of 360-2000 nm. Both light sources have a spot size of approximately 1.5 mm and an incidence angle of 0 degrees.
2.1.4 Sample and Experiment Apparatus

The bifurcated fiber optic cable connects the lamp and spectrometer to the sample, as shown in Figure 2.3.

![Diagram of Ocean Optics diffuse reflection setup](image)

*Figure 2.3: Ocean Optics diffuse reflection setup. 1) Bifurcated optic fiber  2) Ceramic sample disc  3) Sample material  4) Angular alignment apparatus*

The powder sample is placed in a ceramic sample disc approximately 3mm below the dual fiber end of the bifurcated fiber optic cable. The cup in the ceramic disc is approximately 2.25 mm deep.

2.1.5 LabVIEW

A LabVIEW program is used to interface with the spectrometers and catalogue spectral data for further analysis. A prompt allows altering of the integration time of the spectrometer. All raw reflection measurements are recorded as well as their corresponding wavelength in nanometers and energy in electron-volts. The program takes this raw data, outlined in section 2.2.1, to average a chosen number of spectra and calculates the diffuse reflection spectrum using equation 1.1.
2.2 Powder Characterization

2.2.1 Spectrum Measurements

The incident light is sent from one end of the fiber optic cable, depicted in Figure 1.1 and Figure 2.3, and exits one of the cables on the dual end of the bifurcated cable. A portion of the diffusely reflected light travels through the other cable in the dual end of the bifurcated cable. The light travels through this cable and is then digitized in the spectrometer. The first measurement taken is the background spectrum. A piece of black paper, angled at approximately 45 degrees from the normal of the incident light, is placed beneath the bifurcated optic fiber. The next measurement taken is the reference spectrum, which uses a reflection standard of BaSO_4; it is assumed that the reflection standard is 100 percent reflective. The sample is then loaded in the 2.25 mm deep ceramic disc shown in Figure 2.3. The sample is compressed into the ceramic disc by a glass slide to give a nearly level surface. The angular alignment apparatus is used to level the bifurcated optic fiber so the incident light is normal to the sample. For correct spectra calculations, it is important to have the angle and distance between the optic cable and reference be the same as the angle and distance between the optic cable and the sample. If they differ then the intensity will not be relative to one another and will give incorrect spectra calculations.

Raw data is stored locally on the computer used for experimental measurements, as well as on a USB thumb drive and a personal desktop computer. All data analysis is stored only on the USB thumb drive and personal desktop computer.

2.2.2 Measurement of Bandgap Energy

The bandgap energy of a powder material is found by calculating the absorption spectrum from the diffuse reflection spectrum. Kubelka-Munk theory is employed to calculate the absorption spectrum, or the ratio of the absorption coefficient and the scattering coefficient, as seen in equation 1.9. It is assumed that the scattering coefficient, $s$, is constant over the wavelength region that is measured. The LabVIEW calculated diffuse reflection, seen in equation 1.1 is equivalent to the theoretical calculation seen in equation 1.8. The experimentally determined diffuse reflection is plotted against wavelength or energy and shows an onset of absorption around the location of the bandgap of the material. The absorption spectrum is multiplied by the energy and raised to the power of the inverse bandgap transition exponent. To calculate the bandgap energy, $(\alpha \omega h)^{1/p}$ is plotted against $\omega h$, known as a Tauc plot. There is a distinct linear regime in the Tauc plot which
denotes the onset of absorption. The location on the energy axis where the linear portion crosses is the bandgap energy.

**Chapter 3 – Results**

### 3.1 Raw Diffuse Reflection

The raw diffuse reflection is shown for TiO$_2$, SnS, and In$_{2-x}$Sn$_x$O$_3$ in Figure 3.1, Figure 3.2, and Figure 3.3 respectively. The reflected light is digitized by the CCD with a 14 bit resolution. The diffuse reflection is calculated using this data and equation 1.1.

*Figure 3.1: Background spectrum intensity, reflection standard intensity, and raw reflection of titanium dioxide*
Figure 3.2: Background spectrum intensity, reflection standard intensity, and raw reflection of tin sulfide

Figure 3.3: Background spectrum intensity, reflection standard intensity, and raw reflection of indium tin oxide
3.2 Reflectivity Measurements

The diffuse reflectivity of TiO$_2$ with respect to wavelength is shown in Figure 3.4, followed by the diffuse reflectivity of TiO$_2$ with respect to energy in Figure 3.5. The diffuse reflectivity of SnS with respect to wavelength is shown in Figure 3.6, followed by the diffuse reflectivity of SnS with respect to energy in Figure 3.7. The diffuse reflectivity of In$_{2-x}$Sn$_x$O$_3$ with respect to wavelength is shown in Figure 3.8, followed by the diffuse reflectivity of In$_{2-x}$Sn$_x$O$_3$ with respect to energy in Figure 3.9.

*Figure 3.4: Diffuse reflectivity vs wavelength of TiO$_2$ powder*
Figure 3.5: Diffuse reflectivity vs energy of TiO$_2$ powder

Figure 3.6: Diffuse reflectivity vs wavelength of SnS Powder
Figure 3.7: Diffuse reflectivity vs energy of SnS Powder

Figure 3.8: Diffuse reflectivity vs wavelength of $\text{In}_2\text{Sn}_x\text{O}_3$ powder
Figure 3.9: Diffuse reflectivity vs energy of In$_{2-x}$Sn$_x$O$_3$ powder
3.3 Bandgap Measurements

The Tauc plots for TiO$_2$, SnS, and In$_{2-x}$Sn$_x$O$_3$ are shown in Figure 3.10, Figure 3.11, and Figure 3.12 respectively. A line is included to show the location of the bandgap, outlined in section 2.2.2.

*Figure 3.10: Direct bandgap measurement of TiO$_2$*
Figure 3.11: Indirect bandgap measurement of SnS

Figure 3.12: Direct bandgap measurement of In_{2-x}Sn_xO_3
Chapter 4 – Discussion

Preliminary diffuse reflection trials were done using only the reflection standard of BaSO$_4$ and the ceramic sample disc. The angle of incidence between the bifurcated fiber optic cable and the sample stage was varied. No shift in intensity dependent on wavelength or energy was noted, only an amplitude shift in intensity of light received by the spectrometer. The angle of incidence was then kept normal to provide maximum light intensity and consistent experimental results. The materials used were TiO$_2$, SnS, and In$_{2-x}$Sn$_x$O$_3$. Several trials were taken for these samples but only one experimental trial is used. The trials discarded or unused were due to incorrect procedure during experimentation or unknown circumstances leading to evidently incorrect analysis. Figure 3.4 shows an onset of absorption near 390 nm for TiO$_2$. This corresponds to an energy bandgap of 3.17 eV shown in Figure 3.10, which agrees with the accepted value of 3.2.$^{10}$ Figure 3.6 shows an onset of absorption near 300 nm for SnS. Figure 3.11 shows an indirect energy bandgap value of 1.79 eV, which is considerably different than the accepted value of 1.07 eV.$^{11}$ Tin sulfide also has a direct bandgap at 1.3 eV.$^{11}$ However, using the direct transition exponent with the collected data gave a bandgap value of 3.0 eV. The indirect bandgap value lies within the infrared spectrum, at 1159 nm. All infrared data acquired was limiting itself to no less than 1.1 eV and no more than 1120 nm. This limitation has been attributed to the LabVIEW program. Figure 3.8 shows an onset of absorption near 310 nm. This corresponds to an energy bandgap of 3.9 eV as seen in Figure 3.12. The accepted bandgap value for indium tin oxide is 4 eV, which agrees with the accepted value.$^{12}$

Chapter 5 – Conclusion

Powdered titanium oxide, tin sulfide, and indium tin oxide have been examined and spectral analysis has been performed to determine their bandgap. A diffuse reflectance spectroscopy technique utilizing bifurcated fiber optic cables was used. Bandgap measurements from the bifurcated fiber optic method provide moderate, but promising spectral analysis to determine the bandgap of a substance. The spectral analysis of titanium dioxide and tin doped indium oxide provided accurate data for bandgap measurements. In the case of the tin sulfide, which has an indirect bandgap of 1.07 eV, a new experimental trial should be conducted that correctly acquires spectral data in the infrared region. A difference of 0.72 eV is much too large to accept. Ideally the bandgap energies should agree within no more than 0.05 eV. More substances should be tested to provide a more accurate portfolio for the bifurcated fiber optic method of diffuse reflectance spectroscopy.
Chapter 6 – References


## Chapter 7 – Appendix I

### HR4000 Components Table

<table>
<thead>
<tr>
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<th>Description</th>
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<tbody>
<tr>
<td>1</td>
<td>SMA Connector</td>
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<td></td>
<td>Secures the input fiber to the spectrometer. Light from the input fiber enters the optical bench through this connector.</td>
</tr>
<tr>
<td>2</td>
<td>Slit</td>
</tr>
<tr>
<td></td>
<td>A dark piece of material containing a rectangular aperture, which is mounted directly behind the SMA Connector. The size of the aperture regulates the amount of light that enters the optical bench and controls spectral resolution. You can also use the HR4000 without a Slit. In this configuration, the diameter of the fiber connected to the HR4000 determines the size of the entrance aperture. Only Ocean Optics technicians can change the Slit.</td>
</tr>
<tr>
<td>3</td>
<td>Filter</td>
</tr>
<tr>
<td></td>
<td>Restricts optical radiation to pre-determined wavelength regions. Light passes through the Filter before entering the optical bench. Both bandpass and longpass filters are available to restrict radiation to certain wavelength regions. Only Ocean Optics technicians can change the Filter.</td>
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<tr>
<td>4</td>
<td>Collimating Mirror</td>
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<tr>
<td></td>
<td>Focuses light entering the optical bench towards the Grating of the spectrometer. Light enters the spectrometer, passes through the SMA Connector, Slit, and Filter, and then reflects off the Collimating Mirror onto the Grating.</td>
</tr>
<tr>
<td>5</td>
<td>Grating</td>
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<tr>
<td></td>
<td>Diffracts light from the Collimating Mirror and directs the diffracted light onto the Focusing Mirror. Gratings are available in different groove densities, allowing you to specify wavelength coverage and resolution in the spectrometer. Only Ocean Optics technicians can change the Grating.</td>
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<td>6</td>
<td>Focusing Mirror</td>
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<td></td>
<td>Receives light reflected from the Grating and focuses the light onto the CCD Detector or L2 Detector Collection Lens (depending on the spectrometer configuration).</td>
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<td>7</td>
<td>L2 Detector Collection Lens</td>
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<td></td>
<td>An optional component that attaches to the CCD Detector. It focuses light from a tall slit onto the shorter CCD Detector elements. The L2 Detector Collection Lens should be used with large diameter slits or in applications with low light levels. It also improves efficiency by reducing the effects of stray light. Only Ocean Optics technicians can add or remove the L2 Detection Collection Lens.</td>
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<tr>
<td>8</td>
<td>CCD Detector (UV or VIS)</td>
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<td></td>
<td>Collects the light received from the Focusing Mirror or L2 Detector Collection Lens and converts the optical signal to a digital signal. Each pixel on the CCD Detector responds to the wavelength of light that strikes it, creating a digital response. The spectrometer then transmits the digital signal to the spectrometer operating software application.</td>
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# NIRQuest Spectrometer Component Table

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<td>2</td>
<td>Slit</td>
<td>A dark piece of material containing a rectangular aperture, which is mounted directly behind the SMA Connector. The size of the aperture regulates the amount of light that enters the optical bench and controls spectral resolution. You can also use the NIRQuest without a Slit. In this configuration, the diameter of the fiber connected to the NIRQuest determines the size of the entrance aperture. Only Ocean Optics technicians can change the Slit.</td>
</tr>
<tr>
<td>3</td>
<td>Filter</td>
<td>Restricts optical radiation to pre-determined wavelength regions. Light passes through the Filter before entering the optical bench. Both bandpass and longpass filters are available to restrict radiation to certain wavelength regions. Only Ocean Optics technicians can change the Filter.</td>
</tr>
<tr>
<td>4</td>
<td>Collimating Mirror</td>
<td>Focuses light entering the optical bench towards the Grating of the spectrometer. Light enters the spectrometer, passes through the SMA Connector, Slit, and Filter, and then reflects off the Collimating Mirror onto the Grating.</td>
</tr>
<tr>
<td>5</td>
<td>Grating</td>
<td>Diffracts light from the Collimating Mirror and directs the diffracted light onto the Focusing Mirror. Gratings are available in different groove densities, allowing you to specify wavelength coverage and resolution in the spectrometer. Only Ocean Optics technicians can change the Grating.</td>
</tr>
<tr>
<td>6</td>
<td>Focusing Mirror</td>
<td>Receives light reflected from the Grating and focuses the light onto the CCD Detector or L2 Detector Collection Lens (depending on the spectrometer configuration).</td>
</tr>
<tr>
<td>7</td>
<td>InGaAs Detector</td>
<td>Each pixel on the detector responds to the wavelength of light that strikes it. Electronics bring the complete spectrum to the software.</td>
</tr>
</tbody>
</table>