1.0 Learning Objectives

After successfully completing this laboratory workshop, including the assigned reading, the lab write up, the lab quizzes, and any required reports, the students will be able to:

1. Measure the bandgap of a semiconductor by linear fitting of its absorption spectrum edge.
2. Measure the bandgap of a semiconductor by studying the photoluminescence spectra.
3. Distinguish between direct and indirect bandgap semiconductors
4. Utilize the mathematical relationships between incident and transmitted light intensity and absorption constant.
5. Convert easily between wavelength and energy spectra.

2.0 Photons absorbed by semiconductor

As you learned in the solar cell experiments, when the light is shining on a semiconductor sample, if the energy of the individual photons is greater than the semiconductor band gap, then the photons can be absorbed, transferring their energy to an electron. This process, as illustrated in Fig.1, elevates the electron from the valence band into the conduction band. The absorption process therefore creates an electron-hole pair (EHP), because it results in an electron in the conduction band, and a hole in the valence band.

A physical picture of EHP generation is to see the valence band electron as part of a covalent bond. When the covalent bond is broken, the electron is free to move in the crystal lattice of the semiconductor (it is now in the conduction band). The energy required to break a covalent bond is $E_g$. If the photon energy is less than $E_g$, it doesn’t carry enough energy to break a covalent bond and free an electron for conduction. Since electrons cannot occupy the forbidden states between the valence and conduction bands, a photon with energy less than $E_g$ cannot be absorbed and will pass through the sample. In other words, an electron must either be in a covalent bond or free, not in between.

In order to study the bandgap of a semiconductor, we can use light with variable photon energy near the band gap energy. We can then observe that light with lower energy photons (long wavelength) is not absorbed and light with higher energy photons (short wavelength) is absorbed. The photon energy at which the transition between absorbing and non-absorbing behavior takes place will correspond to the band gap energy. Because the transition between absorption and transmission is gradual, we will see that the shape of the transition will provide insight into some of the details of the electron interband transitions (this is a transition between energy states in valence band and conduction band). The transition region is called the ‘absorption edge’. Referring to Figure 1, one can see the reason for gradual nature of the absorption edge. Consider the
number of electrons available to make a transition from valence band conduction band when \( E_p = E_g \). Only those electrons exactly at \( E_v \) can make the transition. As \( E_p \) increases above \( E_g \), more and more electrons from the valence band can possibly make the transition, so the overall probability of a photon being absorbed increases. Thus the number of photons absorbed increases.

Fig.1 Optical absorption in a semiconductor

3.0 Optical absorption, reflection, transmission and scattering

In this experiment, we will be shining light of various wavelengths on a silicon sample as well as a GaAs sample. The transmitted light is then measured by a photodetector. By observing the wavelength at which the sample begins to absorb the light, we will determine the bandgap of the sample.

In order to accurately measure the absorption, we must account for all of the light incident, reflected, transmitted or scattered by the sample, sample holder and other apparatus. Figure 2 provides definition for the various terms describing the status of light in the experiment.

Fig. 2 Shinning light status on a sample
The light enters the sample at x=0 is
\[ I(0)=I_0(1-R) \] (eqn.2)

\( I_0 \) is the total incident light intensity and \( R \) is the fraction of light reflected at the front surface. For unpolarized light at normal incidence (perpendicular) to a flat surface, the fraction of light reflected is given by:
\[ R=(n-1)^2/(n+1)^2 \] (eqn. 3)

Where \( n \) is the index of refraction of the material. For silicon with \( n=3.874 \) at wavelengths near 1\( \mu \)m, \( R=0.348 \), for GaAs, \( n=3.59 \), for GaP, \( n=3.3 \) for this range of wavelengths.

The light intensity, which is a measure of the flux of photons in the optical beam, decreases through the sample as the photons are absorbed. Because there is a uniform probability of absorption throughout the sample, the intensity reaching any distance \( x \) into the sample is
\[ I(x)=I_0 e^{-\alpha x} \] (eqn. 4)

Where \( \alpha \) is the optical absorption coefficient, which is a strong function of wavelength. Large values of \( \alpha \) indicate strong absorption, and small values of \( \alpha \) indicate weak absorption (negative values of \( \alpha \) would imply amplification, but that shouldn’t happen in this experiment.)

Finally, taking into account the reflections from both the front and the back surfaces of the wafer, we can write the expression for the amount of light \( I_t \), which is transmitted through the sample as
\[ I_t=I_0(1-R)^2 e^{-\alpha L} \] (eqn. 5)

Where \( L \) is the sample thickness. Eqn. 5 ignores the small amount of light that will be reflected multiple times within the sample, but this is a small effect, particularly when \( \alpha \) is large. Using Eqn.5, we see that we can determine \( \alpha \) by measuring transmitted light intensity if we know the incident light intensity light \( I_0 \), the sample thickness \( L \), and the sample index of refraction \( n \), which determines \( R \). It will also be convenient to define a transmissivity (\( T \)) as
\[ T(\lambda) = \frac{I_t(\lambda)}{I_0(\lambda)} \] (eqn. 6)

Ideally we could have the maximum transmission through the sample at long wavelengths where there is no absorption
\[ T_{\text{theoretical, max}}=(1-R)^2 \] (eqn. 7)

Several effects will reduce our measurement of transmission from the maximum value (\( T_{\text{max}} \)). One effect, the wavelength dependent absorption of light by the sample, is the quantity we are trying to measure. Unfortunately, there will also be light scattering loss due to roughness, dust, etc. We start with the raw measurements of effective transmission (\( T_{\text{raw}}(\lambda) \)) which is the ratio of light power measured through the sample to light power without the sample:
\[ T_{\text{raw}}(\lambda) = \frac{P(\lambda)_{\text{through sample}}}{P(\lambda)_{\text{without sample}}} \] (eqn.8)
By measuring the light power in identical systems with and without the sample, all losses which are not dependent on the sample are equal in both measurements, and therefore do not affect the ratio.

\( T_{\text{raw}}(\lambda) \) includes measurement of reflection loss and scattering loss in addition to absorption loss. Reflection loss is not strongly dependent on wavelength. If we assume that scattering strongly wavelength dependent either, only the absorption should change as the wavelength is varied.

At a wavelength with no absorption, we will measure the maximum value of \( T_{\text{raw, max}} \), from which we can define a normalizing parameter

\[
S = \frac{T_{\text{raw, max}}}{T_{\text{theoretical, max}}}
\]  
(eq. 9)

where \( T_{\text{raw, max}} \) is the maximum measured transmission value and \( T_{\text{theoretical, max}} \) is the theoretically expected maximum transmission (Eqn.7). From the assumption that scattering is wavelength independent, we can now normalize all of the measured data so that the effects of scattering are removed.

\[
T_{\text{normalized}}(\lambda) = \frac{T_{\text{raw}}(\lambda)}{S} = e^{-aL}
\]  
(eqn. 10)

While the assumption that \( S \) is wavelength independent is not entirely justified, the data should be greatly improved by applying Eqn. 10 to the raw measured transmission \( T_{\text{raw}}(\lambda) \) to create the normalized data \( T_{\text{normalized}}(\lambda) \).

4.0 Wavelength dependence of \( \alpha \)

It is indicated above that \( \alpha \), the optical absorption coefficient of a semiconductor, will depend on wavelength because of the relationship between absorption and the semiconductor band gap.

1. **Direct Bandgap**
   Direct bandgap semiconductor (such as GaAs obey the relation)

\[
\alpha = K_d (E_p - E_g)^{1/2}
\]  
(eqn. 11)

There is only one proportional constant, because direct bandgap materials do not involve phonons (lattice vibrations) in electron band-to-band transitions.

2. **Indirect Bandgap**
   For direct bandgap semiconductors (such as silicon and germanium), \( \alpha \) takes on the general form of

\[
\alpha = K_{i,a} [E_p - (E_g - E_{\text{phonon}})]^2 + K_{i,e} [E_p - (E_g + E_{\text{phonon}})]^2 \quad \text{if } E_p > E_g + E_{\text{phonon}}
\]

\[
\alpha = K_{i,a} [E_p - (E_g - E_{\text{phonon}})]^2 \quad \text{if } E_g - E_{\text{phonon}} < E_p < E_g + E_{\text{phonon}}
\]

\[
\alpha = 0 \quad \text{if } E_p < E_g - E_{\text{phonon}}
\]

\( K_{i,a} \) and \( K_{i,e} \) are proportionality constants which depend on the units chosen for \( \alpha \) and \( E \). The constant \( K_i \) is representative of the probability of phonon absorption or emission, which must accompany the photon absorption in order to alter the valence band electron’s momentum as well as energy. The term phonon refers to a unit of lattice vibration.
Phonon absorption requires the semiconductor to obtain energy (heat) from its surroundings simultaneously with the electron transition. Because energy is simultaneously coming from two sources, the photon and the phonon, the band-to-band transition can actually occur even though \( E_p < E_g \).

As the photon energy is increased, an alternative mechanism of momentum change becomes possible. In phonon emission, the semiconductor lattice gives up a unit of vibration to its surroundings simultaneously with the photon absorption. It’s much more probable to emit a phonon than absorb one, so we will see \( K_{i,a} < K_{i,e} \).

Because direct and indirect bandgap semiconductors have different exponents in the \( \alpha \) versus \( E_p \) relationship, it should be possible to determine the nature of a semiconductor’s band-to-band transition by observing how \( \alpha \) is changing with \( E_p \). Energy and wavelength of the photon are related by the relation \( E_p = h\nu = hc/\lambda \). \( c \) is the light velocity in the vacuum, \( h \) the Planck constant, and \( \lambda \) the light wavelength. It can be shown that:

\[
E_p \text{ (in eV)} = \frac{1.24}{\lambda \text{ (in microns)}}
\]

**5.0 Photoluminescence**

Photoluminescence is the process whereby photons are absorbed by a semiconductor and released at a later point. If a photon has a high enough energy an electron will be excited from the valence band up to the conduction band generating an electron-hole pair (EHP). The electron then loses energy through lattice scattering until it nears the bottom of the conduction band. The electron will then directly recombine when it falls into an empty state in the valence band, emitting a photon at the same energy as \( E_g \). Direct recombination occurs very quickly, with the mean lifetime of an EHP on the order of \( 10^{-8} \) s. This means that the emission of photons from the semiconductor will stop approximately \( 10^{-8} \) s after excitation has stopped.

In this experiment we will be shining laser light of only one single wavelength on a GaAs sample of semiconductor. The light will be will be absorbed generating an EHP which will undergo collisions resulting in a loss of energy. Once the EHP has reached the bandgap energy the electron and hole will recombine generating a photon at the same energy as the bandgap. The laser used in this experiment is a 10mW HeNe laser emitting

![Photoluminescence](assets/fig_photoluminescence.png)

**Fig. Photoluminescence**
light at 632.8 nm which is greater than the bandgap energy. For this experiment only a single peak should be observed on the output corresponding to $E_g$.

6.0 Power and Intensity
There is a frequent confusion between the meanings of the words “power” and “intensity”. Power has units of watts (W); it is the amount of energy in an optical beam per unit time. If $N$ photons each with energy $E_p$ reached a target in $\Delta t$ seconds, the power reaching the target would be

$$P = \frac{N \times E_p}{\Delta t} \quad (\text{eqn.12})$$

if $E_p$ is measured in joules (J), $P$ will be in watts. The conversion between joules and eV is $1\text{eV}=1.60 \times 10^{-19} \text{J}$.

Intensity ($I$) refers to the amount of power per unit area in a beam of light. It is often convenient to speak of intensity because it does not require us to know the size of the illumination.

7.0 Photodiode
A photodiode is a semiconductor p-n junction diode, which is packaged behind a window. When light shines on the photodiode, its normally negligible reverse bias leakage current is increased. The new reverse bias current in the diode is proportional to the amount of power striking the diode. This fact can be rewritten as

$$I_{\text{photo}} = R \cdot P \quad (\text{eqn.13})$$

where $I_{\text{photo}}$ is the amount of reverse bias current generated in the diode, and $R$ is the “responsivity” of the diode, how many amperes it generates for a given power of incident light.

In order to convert the current generated by the photodiode into a readable voltage, a transimpedance amplifier can be employed. A simple transimpedance configuration is shown in Figure 4.

![Photodiode and transimpedance amplifier](image)

8.0 Apparatus
- Silicon sample, GaAs sample
- Monochromator
- Tungsten lamp source
• Lock-in amplifier
• Light chopper
• Si photodiode
• He-Ne laser

9.0 Experimental Set-up

The figure 5 shows the experimental set-up of the optical absorption experiments. The set-up mainly includes the Tungsten lamp, which the light source, monochromator, light chopper and lock in amplifiers. The detailed function of each equipment and the experimental procedures, please follow the instructors in the lab.

![Experimental set-up for optical absorption](image)

Figure 5. Experimental set-up for optical absorption

Figure 6 shows the experimental set-up of the photoluminescence experiment. The major change from the optical absorption set-up is the addition of the HeNe laser. The light collected comes from the same side as the sample is being illuminated from.

![Experimental set-up for photoluminescence](image)

Figure 6. Experimental set-up for photoluminescence
### 10.0 Calculations

10.1 Calculate the photon energy (in eV) for certain wavelength of light

10.2 Understand the photon absorption spectrum

10.3 Understand the transmission spectrum

10.4 Calculate $T_{\text{theoretical, max}}$, bandgap energy, and absorption coefficient $\alpha$ for each sample

10.5 Plot the graph of transmission vs. photon energy to distinguish the direct bandgap and indirect bandgap samples. For a direct bandgap sample, we expect $\alpha$ to depend on $E_p^{1/2}$, for indirect bandgap, we expect $\alpha$ to depend on $E_p^2$. Thus the relation of $E_p$ and $\alpha$ could be used to determine the direct and indirect bandgap materials.

10.6 Using $\alpha$ calculated previously calculate how much laser light was absorbed by the semiconductors at 632.8 nm and 10mW power.

10.7 Calculate how much power was lost as heat in the photoluminescence setup.

10.8 Compare the measurements of semiconductor bandgap using absorption and photoluminescence techniques. Discuss what are the advantages or disadvantages of each method.

### 11.0 Report

The report should show full understanding of the theoretical background, operation procedures and result data of the experiments. The lab report should include the following several parts:

- Abstract
- Theoretical background
- Materials and equipments
- Lab set-up layout
- Experimental data
- Data calculation and analysis
- Conclusion

### 12.0 References:

   [http://electronicmaterials.usask.ca/](http://electronicmaterials.usask.ca/)