Photoluminescence Spectroscopy

I. Introduction

In this experiment, the energy levels in a semiconductor quantum well structure are investigated using the technique of *photoluminescence* (PL). A laser is used to photoexcite electrons in a GaAs semiconductor and when they spontaneously de-excite they emit luminescence. The luminescence is analyzed with a spectrometer and the peaks in the spectra represent a direct measure of the energy levels in the semiconductor.

GaAs is a popular and useful semiconductor material. The importance of electronic devices using GaAs is second only to devices using the more ubiquitous semiconductor, Si. Since GaAs has a higher electron mobility than Si, it is used for higher-speed electronics. Cell phones use GaAs power amplifiers for generating the output signal at 1.8-1.9 GHz, and 2.5 GHz frequencies. In addition, GaAs has a so-called "direct band-gap," unlike Si which has an indirect band-gap. This results in a strong interaction with light which makes it useful for generating light in LEDs (light emitting diodes) and laser diodes. Alloy of GaAs, especially with Al and In, are used exclusively for sources in optical communication.

All solids, including semiconductors, have so-called "energy gaps" for the conducting electrons. In order to understand the concept of a *gap* in energy, first consider that some of the electrons in a solid are not firmly attached to the atoms, as they are for single atoms, but can hop from one atom to another. These loosely attached electrons are bound in the solid by differing amounts and thus have many different *energies*. Electrons having energies above a certain value are referred to as *conduction* electrons, while electrons having energies below a certain value are referred to as *valence* electrons. This is shown in the diagram where they are labeled as conduction and valence *bands*. The word band is used because the electrons have a multiplicity of energies in either band.[*] Furthermore, there is an energy *gap* between the conduction and valence electron states. Under normal conditions electrons are forbidden to have energies between the valence and conduction bands.
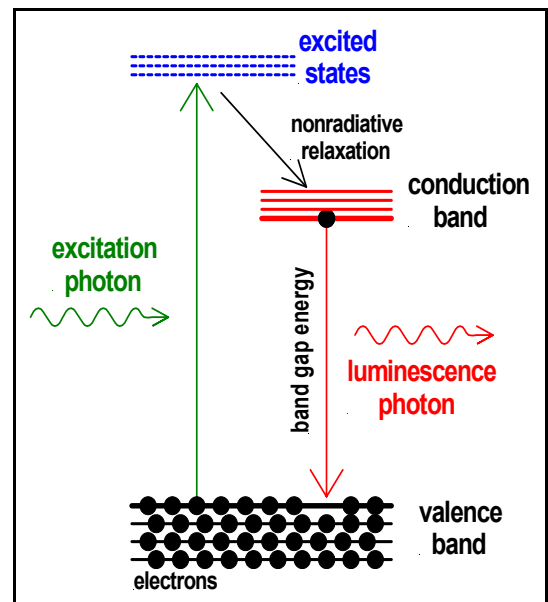
If a light particle (photon) has an energy greater than the band gap energy, then it can be absorbed and thereby raise an electron from the valence band up to the conduction band across the forbidden energy gap. (See diagram.) In this process of photoexcitation, the electron generally has excess energy which it loses before coming to rest at the lowest energy in the conduction band. At this point the electron eventually falls back down to the valence band. As it falls down, the energy it loses is converted back into a luminescent photon which is emitted from the material. Thus the energy of the emitted photon is a direct measure of the band gap energy, E_g. The process of photon excitation followed by photon emission is called *photoluminescence*.

---

[*] Electrons which are mobile in a solid possess kinetic energy which varies with their velocity ($\frac{1}{2}mv^2$). Thus, because of their motion they have a multiplicity of energies and is referred to as a *band* of energies.

This experiment also introduces the widely used tool – the spectrometer – for optical spectroscopy. A spectrometer is a instrument used for measuring the intensity of light as a function of wavelength. Spectrometers usually contain a diffraction grating (or prism) to disperse the light, thereby spreading out the light of differing wavelengths into different positions. The spectrometer unit used here has an internal CCD (charged coupled device) silicon detector, essentially a digital camera detector, to measure the light intensity at various positions along its length. In the figure:

> light from an optical fiber enters at position #1;
> reflects off the collimating mirror #4;
> is diffracted by the grating #5;
> reflects from focusing mirror #6;
> then finally is read out by the CCD detector #9.

For more information on Ocean Optics spectrometers see their website,
http://www.oceanoptics.com/products/2004Catalog.pdf
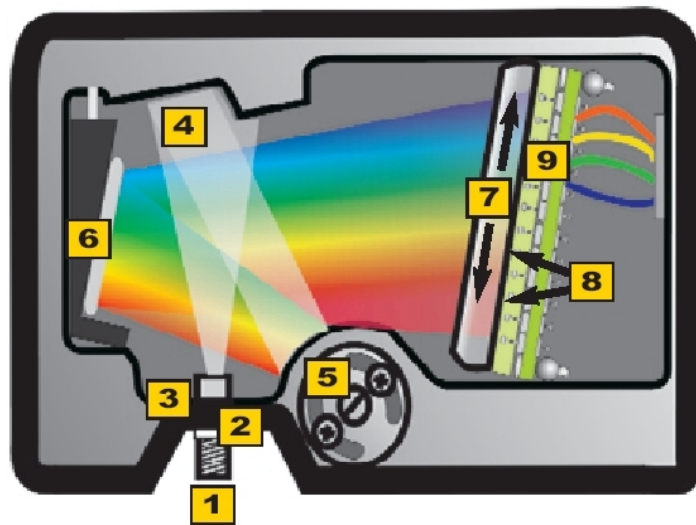
II. Apparatus

> aluminum breadboard with 1/4-20 tapped holes
> green laser diode, 5 mW @ 530 nm
> USB2000-FLG Ocean Optics spectrometer/detector, USB cable
> OOIBase32 software
> lens, 25 mm focal length, for collecting and focusing fluorescence
> mirror, in x-y adjustable mount
> neutral-density (ND) optical filter (black)
> long-pass optical filter (yellow)
> optical fibers, 50 and 600 micron cores
> GaAs/GaAlAs sample mounted on holder

III. Procedures

A. *Room Light Spectrum*

Here, you will measure the spectrum of fluorescent light in the room in order to determine the gases in the tubes. Insert one end of the 600 micron core fiber optic (FO) into the spectrometer input and the other end pointing at the wall to collect stray room light. Plug in the USB cable and start the software. Adjust the collection (integration) time so that the highest spectral peak is near but not above saturation at 4000 counts. You should see many spectral lines from the excited gases in the fluorescent ceiling lights.

> Store the spectrum and include in report.
> What is the characteristic *linewidth* (full-width at half-maximum) of the narrowest spectral line?
> Replace the 600 micron FO with the 50 micron FO. What is the narrowest linewidth? Explain.
> Identify and list in table form the intensities of the 5 or 6 strongest lines in **counts per second**.
> List the measured wavelengths and identify the *element* by their corresponding wavelength.

B. *Optical Setup*

Mount the optical components on the breadboard approximately as shown in the diagram and photograph. **Before beginning, confirm that the black neutral-density (ND) filter is in front of the laser.**

> Adjust the center of all components to a common height to within a few mm.
> Aim the laser beam onto the small sample of GaAs.
> Place a beam stop to keep the reflected beam from leaving the table.
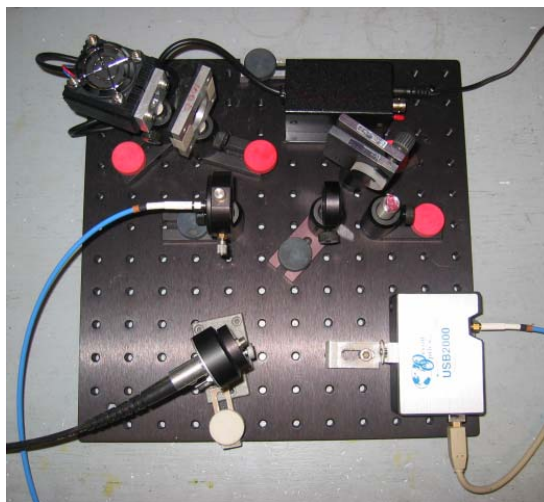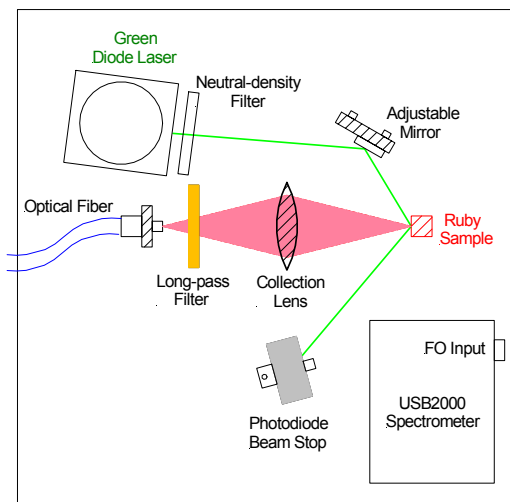
Gross Alignment – Next, the collection optics must be aligned. Using the *lens maker's formula*, compute the image and object distances for the f=25 mm focal length collection lens and place the lens accordingly. Insert one end of the 600 micron FO into the mount that points at the collection lens, and then shine a white light source into the other end. While holding a white piece of paper at the front of the small GaAs crystal, adjust the position of the lens and FO so that the white spot image is focused at the front face of the crystal. Now adjust the mirror to overlap the green laser beam and the white spot image on the crystal. Cover the breadboard with the black cloth to block the room light.

Fine Alignment – Maximize the PL spectral peak from the GaAs by adjusting the mirror.

C. Pure GaAs

Insert the 50 µm core FO and make fine adjustments to maximize the PL.
Collect and store the PL spectrum from the pure GaAs sample (small top piece).

> What is the wavelength of the spectral peak and full-width at half-maximum (FWHM) linewidth?
> Plot PL intensity versus photon energy in energy units of eV (transform x-axis).
> Compute and record the peak position, E_o, and FWHM, γ, in eV.

D. GaAs Quantum Well

Move the sample holder in order to collect PL from the quantum well sample (small lower sample).
Collect and store the PL spectrum for the GaAs quantum well.

> What is the wavelength and FWHM of the spectral peak?
> Plot PL intensity versus photon energy in energy units of eV (transform x-axis).
> Compute and record the peak position, E_1, and FWHM, γ, in eV.
> Compare E_1 to $E_g + \Delta E$ (use $E_g = 1.413$ eV).
> Compute the well width and uncertainty. Discuss.

Background

The diagram on the right shows a *quantum well* structure made of layers of GaAs and the alloy $Ga_{0.7}Al_{0.3}As$ (or abbreviated GaAlAs). Adding aluminum to GaAs increases the bandgap. For simplicity it is shown with all the energy increase in the conduction band. Thus in this sandwich of materials, GaAs forms a *well* of lower energy with GaAlAs *barriers* on either side. If the well is sufficiently narrow then the conduction band is effectively pushed up to the double line and this is referred to as *quantum confinement*. The confinement energy is denoted as ΔE, which is equal to the energy increase. Now, electrons which are confined in the well have an energy $E_g + \Delta E$ above the valence band. This new energy is seen as a shift in energy of the PL spectral peak to higher photon energies.
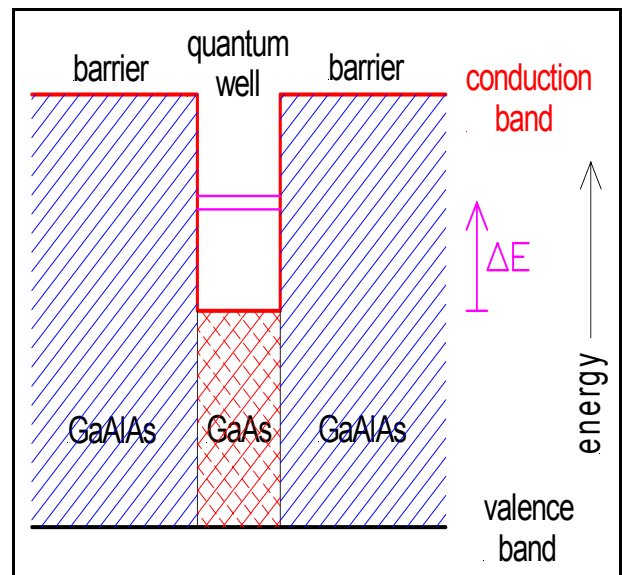
Quantum mechanics tells us that when a particles is confined in space its energy is increased by an amount that depends on the mass of the particle, m, and the size of the confinement region, z. For a planer quantum well with infinitely high barriers the confinement energy is given by

$$\Delta E = h^2 / (8\, m\, z^2),$$

where $h = 6.63 \times 10^{-34}$ J-s is Planck's constant. Here, m is the electron effective mass in GaAs which is much smaller that the free electron mass, $m = 0.068\, m_o$. Substituting these values for a well width $z = 10$nm gives

$$\Delta E = 55\text{meV} / (z/10\text{nm})^2.$$

> Show how this formula was obtained? (Do the math, 1 eV $= 1.60 \times 10^{-19}$ J).

IV. Appendix

A. Lens Maker's Formula

The lens maker's formula is used here to determine the parameters for focusing the image of the GaAs PL into the optical fiber.

Convex focusing lens are useful for projecting an image of an object from one side of a lens onto the other side. See the diagrams below. The distance of an image from the lens is related to the distance of the object from the lens by the *lens maker's formula*,

$$1/i + 1/o = 1/f,$$

where i is the image distance, o the object distance, and f the focal length of the lens. The magnification of the lens is $M = i/o$. A special case of this formula is the focusing of a collimated laser beam. There the object distance is infinite, so the laser beam is focused to a small diameter spot at a distance $i=f$ from the lens.