

# Scanning Tunneling Microscopy

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(Dated: April 11, 2016)

## I. INTRODUCTION

Scanning tunneling microscopy (STM) images surfaces of materials at sub-angstrom level resolution by applying a bias voltage to a sharp tip very close to the sample. The bias voltage allows an electron to tunnel across this potential difference between tip and surface without the two ever making direct contact. The tip experiences a current as a result of the electron transfer. This current changes in response to the local density of electron states as the tip moves across the material. The resulting image from tracking tunneling current as a function of position can measure atomic scale features of a surface, such as geometric patterns, lattice constants, and bond lengths. Binnig and Rohrer developed this technology while at IBM Labs (Physical Review Letters, 1982) and earned the Nobel Prize in Physics in 1986.

We used a NanoSurf NaioSTM to capture STM images of the surface of graphite. We prepared the STM by sterily making the scanning tip, cleaning the graphite, and aligning the sample. We carefully approached the tip the the sample, making sure that the tip never came into contact with the surface of the graphite. Once we had a sufficiently sharp tip and found a good section of the graphite to scan, we routinely zoomed in until we reached a nanometer sized image. From this high resolution image, we observed the hexagonal pattern of graphite and a lattice constant of BLANK.

## II. BACKGROUND THEORY

To study energy levels characteristic to the semiconductors analyzed in this experiment, we analyzed the photoluminescence that occurs when the samples are hit with a laser. Photoluminescence occurs when a photon excites valence electron in the material to an excited state and then emits a photon as it returns to the valence band. The electron contains follows the energy-momentum relation:

$$E = \frac{1}{2}m_0v^2 + m_0c^2 \quad (1)$$

of the energy being the classical kinetic energy and the rest energy. This excited state is not stable and the electron loses non-radiative energy and enters a lower energy state in the conduction band. When the electron returns from this energy state to the valence level, photons at specific energy levels are released, resulting in photoluminescence. The observed energy of the luminescence

photons is a measurement of the sample's band gap energy.

Semiconductors can have either a direct or indirect band gap. In a material, the atoms arrange in a crystal lattice. To jump from valence to conduction bands, the electron must travel from the maximum energy state in the valence band to the minimal energy state in the conduction band. Making this transition from valence to conduction band requires enough quasi-momentum (aka crystal momentum) within the lattice.

$$p = \hbar k \quad (2)$$

Direct semiconductors have a quasi-momentum vector that is aligned between the energy maxima in the valence band and the energy minima in the conduction band. When the quasi-momentum is not the same between the higher and lower energy bands, the electron needs additional energy to reach to conduction band due to the conservation of momentum. This additional energy comes from an interaction with a phonon. This configuration occurs in indirect semiconductors, where the electron requires additional thermal energy for oscillation from a phonon. Photon emission from indirect semiconductors is more unlikely than from direct semiconductors because of this required phonon-electron interaction. An example of an indirect material is silicon. These differences are illustrated by the band plots in Figure The band plot displays the relationship between the energy (y axis) and momentum (x axis) of the system.

Fluorescence spectroscopy analyzes the photoluminescence emitted from a sample. A laser shines on the sample and provides the energy required for electron excitation. The sample then emits photons at characteristic wavelengths, which are captured using a spectrometer (specific set up described in Material and Methods section). This technique provides information on the chemical compounds of the sample, useful in chemistry, biology, and electronics. In addition, the doping of semiconductors allows designers to control exactly which wavelength of light is emitted, which can be very useful for specific applications (i.e. colored LEDs, tagging samples using fluorescent dyes).

Quantum dots act as nanoscale semiconductors. At a scale of less than 100 nm, the band gap energy becomes higher. These nanoparticles confine electrons and form a standing wave within the particle (see figure

The energy levels are modeled using the standard quantum particle in a box problem with confined energy:

$$E = \hbar\omega = \frac{\hbar^2 k_n^2}{2m} = \frac{\hbar^2 \pi^2}{2\mu a^2} \quad (3)$$

where  $a$  is the nanoparticle radius,  $\mu$  is reduced mass of the electron, and  $k_n$  is the wavenumber  $\frac{n\pi}{a}$ . The total energy of the system is the summation over the band gap, confinement, and intrinsic Coulomb energies. Adjusting the diameter of the nanoparticles allows for easy control of the luminescent color. Because they are so easy to control, quantum nano-dots have been rapidly adopted in fields such as biology (better alternative to bio-tagging samples), quantum computing, LEDs, and more efficient solar cells.

### III. MATERIALS AND METHODS

We arranged our spectroscopy components on an aluminum bread board. A green laser passed through a focusing lens to hit an adjustable mirror. This mirror allowed us to minutely move the laser's deflection to hit the provided sample at  $45^\circ$ , where the laser's reflection would then be ended using a beam stop. A lens focused the photoluminescence streaming from the sample before the emitted photons were finally captured by an optical fiber that fed into the USB2000-FLG Ocean Optics spectrometer. Gross alignment of lenses and sources were dictated by the lens maker's formula:

$$\frac{1}{i} + \frac{1}{o} = \frac{1}{f} \quad (4)$$

, while we fine tuned this alignment using knobs on each piece of equipment that allowed for slight movement. In order to minimize interference from the strong laser, a 590 nm long pass filter was placed in between the photoluminescence beam and the optical fiber. The collected beam was fed into the computer where we analyzed the energy spectrum using SpectraSuite software.

We began by collecting ambient room light, which contains a variety of spectral lines from the multiple elements in the ceiling bulbs. We then shined the laser on the first sample GaAs (Gallium Arsenide) to observe the direct semiconductor's band gap energy. Next, we repeated this procedure on direct semiconductor InP (Indium Phosphide). We then collected the spectrum of alloy InGaP (Indium Gallium Phosphide). InGaP is not uniquely direct or indirect and its band gap energy depends on the concentration of each element in the semiconductor. Knowing its energy dependence function, we calculated the Ga concentration within InGaP. Finally, we replaced the semiconductors' mount with a sample containing CdTe (Cadmium Telluride) nanoparticles. We measured the energy shift from the photoluminescence spectrum. Calculating the energy allowed us to find the nanoparticle's diameter by using equation 3.

### IV. RESULTS

Figure shows the room light spectrum of wavelength (nm) v intensity (counts).

The FWHM of the narrowest line (apparatus resolution) is 10.54 nm. From figure 1, we identified the four most prominent peaks by highest intensity. The

We then placed the optical collection fiber into the set up described in and shined the laser onto the GaAs, InP and then GaInP samples successively. All three spectra are shown in All captures were taken with an integration time of 20ms, so their relative intensities are comparable.

We transformed each spectra from wavelength to energy (shown in figure 7) knowing:

$$E = \frac{hc}{\lambda} \quad (5)$$

The analysis of the wavelength and energy spectra are outlined in Table 2.

InGaP is an alloy of the semiconductor InP. InP is doped with certain concentrations of Ga to output specific wavelengths based on the polynomial dependence:

$$E'(x) = E_o + 512x + 603x^2 \quad (6)$$

where  $x$  is the Ga concentration and  $E_o$  is the band gap energy of InP. Based on the InP and InGaP energies recorded in Table 2, we determined the alloy concentration,  $x$ , to be  $0.61 \pm 0.14$ . If we desired our InGaP sample to produce orange light (590 nm), we would create the alloy with a  $0.77 \pm 0.07$  Ga concentration.

Finally, we captured the photoluminescence of CdTe nanoparticles (quantum dots), figure 8.

The wavelength of the central peak exists at  $608.05 \pm 10.54$  nm. The energy peak occurs at  $2038.50 \pm 179.64$  meV. Using equation 3 with an  $E_o$  of 1.49eV, we calculated the average diameter of the nanoparticles to be  $5.21 \pm 0.07$  nm.

### V. DISCUSSION

Photoluminescence spectroscopy collects information about a sample's chemical and physical make up. When excited (in our experiment by laser), each sample produces fluorescent light as electrons in the material return from a higher energy to the valence state. When captured, this released light shows distinct spectral lines where the central peak on the plot is the band gap energy of the material. The band gap energy is a defining characteristic of a material and can be used to identify unknown samples. In reverse, doping semiconductors to create alloys allows the user to produce photoluminescence at desired energies. This technique is central to the creation of LEDs, useful in bio-tagging, and solar cells.

We observed photoluminescence in both ambient and sampled light. We analyzed the wavelength spectrum to find the most prominent peaks in room light. These characteristic peaks give us insight into which materials are in the light bulbs. We found elements used commonly in semiconductors. We then carefully configured

our optical set up to shine a laser on three semiconductor samples: GaAs, InP and InGaP. The laser hit the sample at  $45^\circ$ , which excited the electrons in the sample. Upon de-excitation, the samples produced a perpendicular photoluminescence stream. The light from the sample was focused through a lens before being captured by the spectrometer.

From the central peak on the wavelength spectrum, we calculated the primary band gap energy using equation 5. GaAs and InP are both direct semiconductors. Direct semiconductors release energy more easily than indirect semiconductors as they don't require extra energy from phonons to jump from the valence band to an excited state. InGaP can be a direct or indirect semiconductor based on the Ga concentration in the alloy. The output energy has a polynomial dependence on Ga concentration (equation 6). We found the band gap energy of GaAs to be  $1445.85 \pm 136.73$  meV, comparable to the accepted value of 1424 meV. We calculated the InP energy  $1345.18 \pm 96.58$  meV, again within uncertainty to the accepted 1344 meV. The band gap energy of InGaP varies. To find the concentration of Ga in our InGaP alloy, we used our observed band gap energy of  $1883.7 \pm 83.78$  meV to calculate a Ga concentration of  $0.61 \pm 0.14$ . Finally, we illuminated nanoparticles, which can capture photons and form standing waves. The diameter of these nanoparticles controls the energy of light released. With an energy of  $2038.50 \pm 179.64$  meV, we found the average diameter to be  $5.21 \pm 0.07$  nm.

The intensity of the observed spectrum is heavily dependent on the precise alignment of the optical board. Certain semiconductors release energy more easily than others. We cleaned the sample to prevent dirt and oil from preventing photoluminescence. To prevent other spectra from entering the spectrometer, we placed a beam stop in the path of the reflected laser and covered

the experiment with a black cloth.

## VI. CONCLUSION

We collected spectra of room light, a variety of semiconductor samples, and CdTe nanoparticles. We began by identifying materials in the room lights. The four main peaks identified in the room light were GaAsP, GaN, AlGaInP, and ZnSe. Then, we carefully aligned our optical set up (shown in figure ??). We shined the laser on each sample and consecutively and captured the emitted photoluminescence. The results and comparable values in literature are displayed in Table 3.

Material	Band Gap Energy (meV)	$\sigma$	Known Value (meV)
GaAs	1445.85	136.73	1424
InP	1345.18	96.58	1344
InGaP	1883.7	83.78	Variable

Finally, we analyzed the outputted light from CdTe nanoparticles. Knowing that the standing wave formed in the nanoparticle acts like the classic quantum mechanics problem of particle in a box (equation 3), we calculated the average diameter of the CdTe particles in the sample. The central energy peak of  $2038.50 \pm 179.64$  meV suggests a diameter of  $5.21 \pm 0.07$  nm.

## VII. BIBLIOGRAPHY

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