Surface Plasmon Resonance: Theory and Method Development at the University of Wisconsin – Stout

Moehring, Nicole; Klavekoske, Andrew; Hollinger, William; Zimmerman, Todd*

**Department of Chemistry and Physics at the University of Wisconsin – Stout*

Abstract

Surface Plasmon Resonance (SPR) is a popular technique that takes advantage of wave behavior at an interface to detect and/or identify a material. A method for understanding how SPR can be used to characterize thin metal films has been developed based off the Kretschmann configuration. An optimized set-up consisting of an LED light source, photodiode, multimeter, and series of lenses is developed for quantitatively measuring plasmon resonance. This apparatus is used to take measurements relating the incident angle to reflectance for silver and gold samples of various thicknesses. These thicknesses were measured using Atomic Force Microscopy (AFM). Three variables known to influence SPR are investigated: film thickness, type of metal and source light intensity. The data is presented and discussed and suggestions for future developments are proposed.

I. Introduction

Plasmonics, the study of the electromagnetic responses of materials, is an ever-growing field. Surface Plasmon Resonance (SPR) is a subtopic which has received much attention since its rapid adoption in the early 1990's, though the method often used in applications was developed in 1971. SPR can be used to enhance surface sensitivity of spectroscopic measurements, identify thin metals film, nanoparticles, and molecules, and sense changes in environment. The researchers of this paper chose to focus on using SPR to characterize thin films.

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Surface Plasmon Resonance results from the interaction between surface plasmons and evanescent waves. An evanescent wave is a portion of the incident light which sits at the surface in the form of an electromagnetic field. These waves form when light is totally internally reflected and decays exponentially as distance from the interface increases. The wave function of this evanescent wave is described by:

$$k_{evan} = \frac{2\pi}{\gamma}(n_1 \sin\theta) \qquad 1.1$$

should be lamda (λ) not gamma (γ) for wavelength

Include graphic to show these variables

where γ is the wavelength of the incident light, n_1 is the refractive index for the material with a higher refractive index, n_2 is the refractive index for the material with a lower refractive index, and ϴ is the incident angle. A surface plasmon is a quanta of surface energy that forms when free electrons in the metal film are excited and oscillating. The Drude-Sommerfeld Model describes the behavior of a free-electron gas and explains how the electrons behave at the interface between a metal and a dielectric material. At this interface there are surface charge density oscillations that occur which give rise to plasmons. The wave function of surface plasmons can be described by:

$$k_{SP} = \frac{2\pi}{\gamma}\left(\sqrt{\frac{n_2^2 n_1^2}{n_2^2+n_1^2}}\right) \qquad 1.2$$

where γ is the wavelength of the incident light, n_1 is the refractive index of the material with a lower refractive index, and n_2 is the refractive index of the material with the higher refractive index.

Resonance occurs when the evanescent wave and surface plasmon wave couple, i.e. when the energies of the two waves match, allowing the evanescent wave to excite the surface plasmon and convert it to an energy phonon or photon. This coupling occurs at an incident angle greater than the critical angle, $\Theta_{critical}$, which means the incident light is undergoing total internal reflection (TIR). Total internal reflection occurs when the medium on the other side of the boundary has a lower index of refraction than the medium the wave initially travels through. This is shown in figure ##. The critical angle is calculated using a variation of Snell's Law:

Double-underlines mean to Capitalize the underlined Word

$$\theta_{critcal} = \sin^{-1}\left(\frac{n_t}{n_i}\right) \tag{1.3}$$

where n_i is refracted index of incident medium. n_t is refracted index of transmitted medium. $\theta_{critcal}$ is incident angle at which total internal reflection occurs.

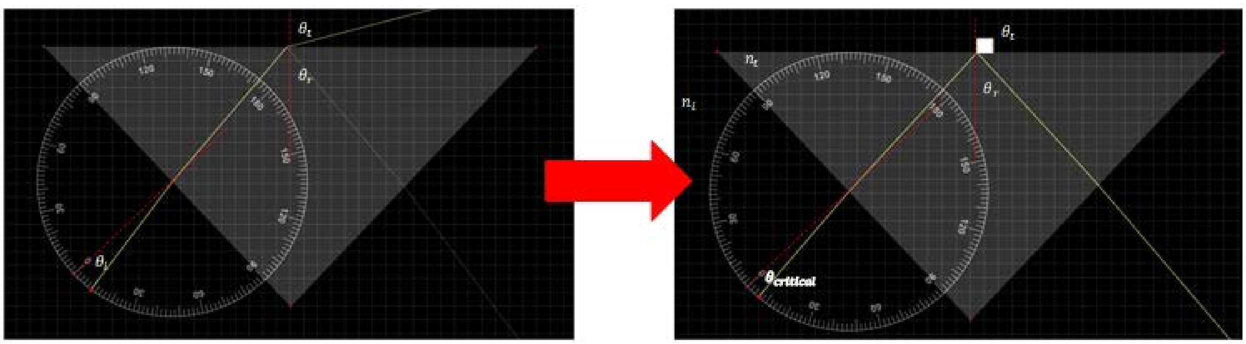


Figure 1.1: Diagram of total internal reflection in a prism[8]

Total internal reflection of parallel light is further explained by Fresnel's Equations which depict the behavior of light when travelling across differing media. The percentage of transmitted and reflected power are given by:

$$P_t = \left(\left(\frac{n_t \cos\theta_t}{n_i \cos\theta_i}\right)\left(\frac{2n_i \cos\theta_i}{n_t \cos\theta_i + n_i \cos\theta_t}\right)\right)^2 \tag{1.4}$$

$$P_r = \left(\left(\frac{n_t \cos\theta_i - n_i \cos\theta_t}{n_t \cos\theta_i + n_i \cos\theta_t}\right)\right)^2 \tag{1.5}$$

where n_i is refracted index of incident medium. n_t is refracted index of transmitted medium. θ_i is incident angle. θ_t is transmitted angle. P_t is the percentage transmitted power, P_r is the percentage reflected power. Fresnel's equations show us that as you approach the critical angle for total internal reflection the transmitted power goes to 0% and the reflected power goes to 100%.

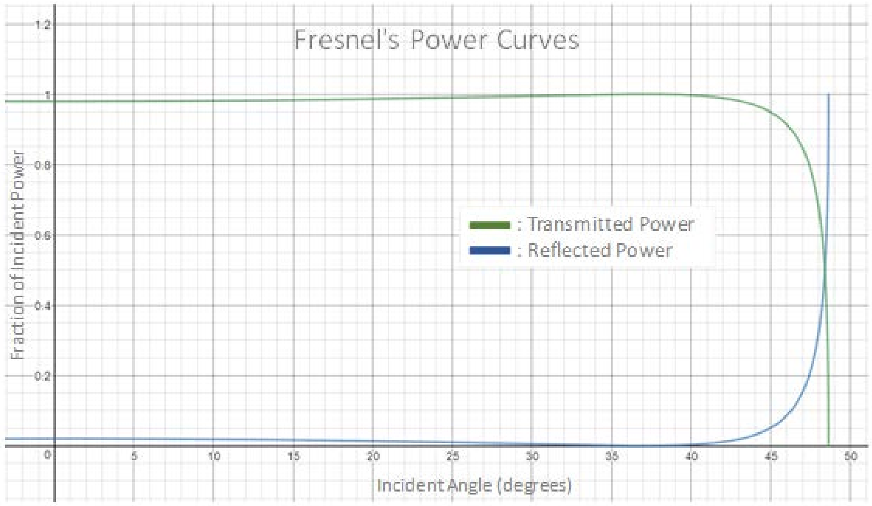


Figure 1.2: Graph of fraction of incident power vs incident angle, showing the transmitted and reflected curves.[7]

The incident angle at which resonance will occur, Θ_{SPR}, occurs when $k_{evan} = k_{SP}$. By setting equations 1.1 and 1.2 equal, we get the incident angle at which surface plasmon resonance will occur, Θ_{SPR}:

$$\theta_{SPR} = \sin^{-1}\left(\frac{1}{n_1}\sqrt{\frac{n_2^2 n_1^2}{n_2^2+n_1^2}}\right) \qquad 1.6$$

The angle of incidence necessary for plasmon resonance calculated from equation 1.6 utilizes the refractive indices of glass and gold. However, because the gold film is thin and not uniform, the refractive index for gold retrieved from other sources may not be accurate. Another way to calculate the resonance angle without using the refractive index value for gold is derived from Snell's law.

$$\theta_{SPR} = 45 - \sin^{-1}\left(\left(\frac{n_t}{n_i}\right)\sin\theta_{i,air}\right) \qquad 1.7$$

where n_i is refracted index of air. n_t is refracted index of the prism.θ_{SPR} is incident angle at the glass to gold interface. $\theta_{i,air}$ is incident angle at the air to glass interface. The derivation of this equation is depicted below in figure ##:

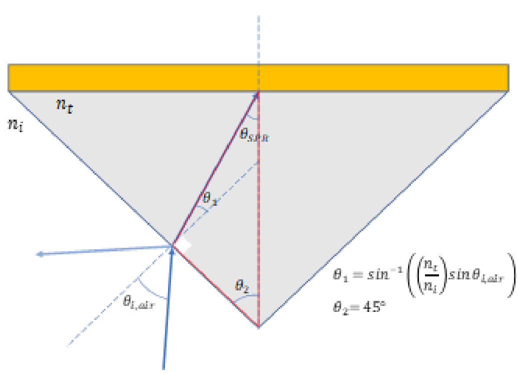


Figure 1.3: Diagram of the θ_{SPR} derivation

Equation 1.6 illustrates that the incident angle at the glass-gold interface necessary for plasmon resonance is dependent upon the refractive indices of the two materials. It is known that the refractive indices of the materials are influenced by the mass and density of any molecules absorbed to the surface. Therefore, if a sample were to be measured before and after a molecule has been absorbed to the sample surface, a noticeable and measurable shift in Θ_{SP} would be seen. As a result, methods for characterizing thin films and identifying absorbed molecules using surface plasmon resonance has been developed.

The Otto method and Kretschmann method, shown in figure ## are two well developed methods for measuring surface plasmon resonance, the latter being more popular because it does not require an air gap between the prism and metal film. This additional variable employed in the Otto method has the potential to introduce more uncertainty to the measurements as the spacing can be difficult to measure and control with accuracy. Also, this method is significantly more prone to damping (dissipation of energy), as the magnitude of damping is influenced by film thickness and the size of the air gap. For this reason, the researchers chose to develop their methodology based off the Kretschmann method.

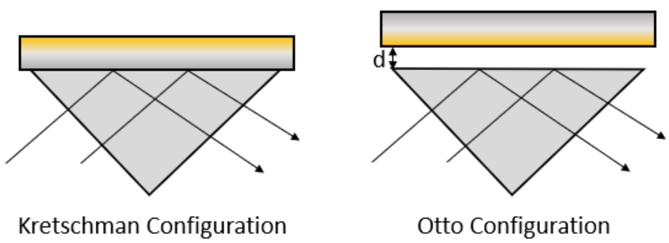


Figure 1.4: Illustration of the Kretschmann and Otto configurations used when measuring surface plasmon resonance

Using this information, the research team at the University of Wisconsin Stout developed a series of experiments to understand how surface plasmon resonance can be used to characterize thin metal films. The first task was to build a reliable setup for collecting data. This setup was then used to measure and evaluate how metal film thickness, type of metal film, and source light intensity effect surface plasmon resonance intensity. An additional experiment was developed to measure the thickness of the gold film that results from sputter coating. The procedures and results are detailed in the following sections.

II. Materials and Methods

A. *Light Table Setup*

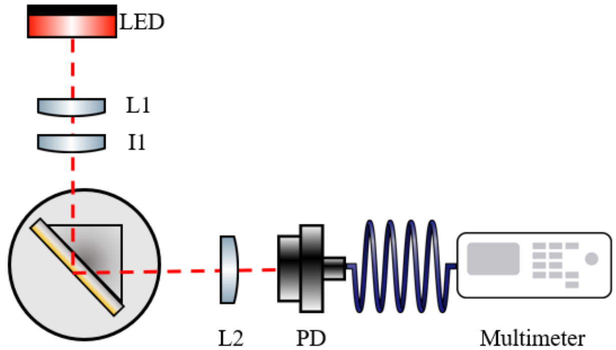


Figure 2.1: Schematic of the set-up used.

Figure ## is a schematic of the setup used to observe and collect data on surface plasmon resonance and figure ## is photos of the setup. This setup utilizes the Kretschmann method to measure the intensity of reflected light. The incident light (LED) has a typical actual wavelength of 634 nm (ThorLabs Mounted LED, 625 nm). This light is uncollimated before passing through a 200 mm ThorLabs lens (L1). For experiments that need uncollimated light, this lens can be removed. A ThorLabs iris (I1) is also attached. These components are stationary on the light table. A *(insert prism details)* and thin film sample are held stationary on a rotating stage using a pressure clamp. This stage can measure changing angle with precision to 1/20th of a degree. Any light that is reflected will pass through a 30 mm ThorLabs lens (L2), focusing the light onto the photodetector (PD) which converts the light into a value of electrical potential that can be read on the screen of a Fluke 45 dual display multimeter. L2 and PD are stationary relative to each other but are on an arm that can be rotated around the same axis as the prism. This allows us to chase the reflected light.

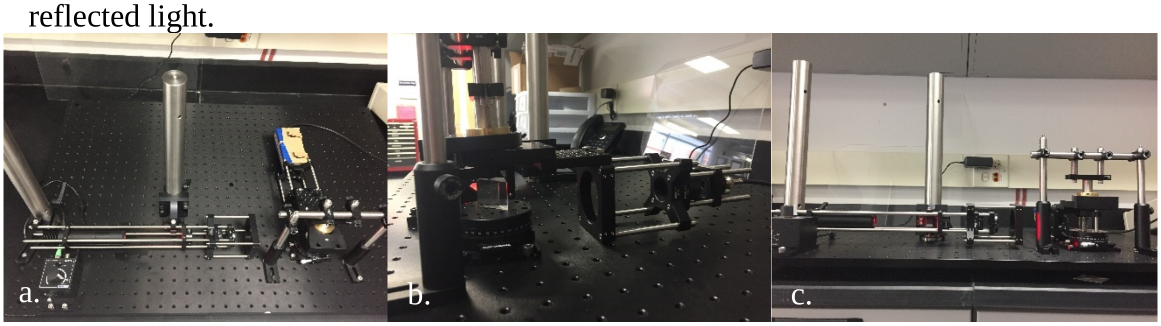


Figure 2.2: a. overhead view of the whole setup. The stationary arm holding the light source is on the left and the rotating arm with the photodiode attached is on the right. b. front-side view of the setup. The incident light can be seen on the right and the prism attached to the rotating stage is on the right. c. close-up of the rotating arm which is suspended.

With this setup, we can measure how very small changes in the incident angle effect the reflected intensity. We can also measure the reflected angle using the dial on the rotating arm, however the accuracy of these measurements is only to a single degree. It is very important to note that the axis of rotation for the prism and the axis of rotation for the arm must be the same. Using the pressure clamp and the immersion oil ensures that coupling will occur between the waves.

There are some components in this setup that are not ideal. First, when the prism is secured by the pressure clamp, the point at which the incident light is perfectly perpendicular to the side of the prism does not read "0 degrees" on the stage. Since the stage cannot be zeroed, the researchers must take note of the starting value on the stage and measure the change in incident angle relative to that point. Second, the prism and film sample are orientated sideways which means any work done with adsorption of molecules to the film will need to be completed using molecules that will bond to the film. Otherwise, when the sample is turned sideways to take measurements, the molecules will run off. Finally, the 'chase and catch' method described in the following section of this paper introduces additional room for human error if the reflected light is not perfectly focused in the middle of the photodiode.

B. *Incident Angle vs Intensity*

Using the set-up described above, an experiment was developed to test the effect of three variables of interest on reflected light intensity and resonance: 1. thin film thickness, 2. thin film material type, and 3. incident light iris diameter.

1. Film thickness: Metal film thickness has been shown to influence reflected light intensity as the incident angle changes. Gold films of five thicknesses were evaluated. The gold films were deposited onto a clean, glass microscope slide using a Cressington 108-Auto sputter coater. This deposition method uses a magnetron to create a magnetic and electric field which energizes the gold atoms and knocks them loose from the material. These gold ions bombard the substrate, creating a thin layer of gold. The 'auto' mode was utilized when making the thin film samples of different thicknesses. Each 'auto-cycle' runs for 30 seconds. To get thicker films, the cycle was run multiple times. The exact thickness deposited by each cycle is not provided by the manufacturer of the sputter coater so an additional study into the actual film thickness was conducted and is explained in section C of this paper. Gold samples are labeled based on the number of deposition cycles. No pressure clamp was used to hold the prism in place.

2. Film material type: The type of material used for the thin film has an effect on the intensity of the reflected light as well as the incident angle at which resonance occurs. The intensity of light reflected off either a gold or silver film as the incident angle changed was recorded. The 500 angstrom thick silver film was purchased from ThorLabs (part # SSAG500-Q1). No pressure clamp was used to hold the prism in place.

3. Iris diameter: An iris is included in the setup between the incident light source and the prism (figure ##). The purpose of this experiment was to investigate how un-collimated light effects the reflected light intensity and measure the difference between the max and min intensities. We believed we were supposed to be seeing far more dramatic drops in reflectivity than we were achieving. Visually, it seemed that

the resonance band that resulted from un-collimated light was darker than that from the collimated light. Changing the diameter of the iris controlled the amount of un-collimated light that could interact with the prism. The iris diameters were set to 1.25 mm, 5.0 mm and 10.10 mm. A pressure clamp was used to hold the prism in place.

Getting Setup:

- Clean the prism and non-coated side of the sample slide using isopropyl alcohol
- Put a drop of immersion oil on the non-coated side of the slide and attach it to the prism, so that the immersion oil has an almost transparent seal between the two with few air bubbles (this ensures coupling between the waves will occur)
- Align the prism and slide with the junction between the slide and prism in the center of the rotating platform. In early experiments we used a piece of carbon tape to hold the prism in place. This was later replaced with a pressure clamp which holds the prism and slide still
- Turn on the LED light source to full power
- For experiments 1 and 2 described above, the iris is left fully open and L1 is used
- To align the light perpendicular to one side of the prism surface:
    - Without pressure clamp: Set the stage to zero degrees. Point the light at the prism. Some light is reflected back towards the incident light source. A piece of cardboard with a pinhole in the center is placed in front of the iris, so the incident light passes through the hole before contacting the prism. Keeping the piece of cardboard with a pinhole in the center here, the prism is adjusted until the reflected dot lines up directly with the pinhole on the cardboard. Once the reflected light lines up, it means that the prism is perpendicular to the light source
    - With the pressure clamp: Use the same process as above with the carboard but rather than adjusting the prism placement, rotate the stage. When the light is perpendicular, write down the exact degree that the rotating stage is at. This becomes the zero point and changes in incident angle are determined from here.

Collecting Data:

- Estimate the incident angle that resonance occurs at using visual estimation
- Use this estimation to set the range of angles that would be tested, which includes this estimated angle as the middle
- Start from the lowest incident angle (which was usually -4 degrees from perpendicular) and tighten down the rotating platform so that we could use the smaller increments dial. This allows us to rotate our platform at as low as 1/25th of a degree increment. We collected data points every half degree.
- Align the rotatable detector arm so the reflected light is hitting the center of the photo detector. This was done using a THORLabs alignment plate between the L2 lens and photo detector. Make sure the light hits the center of the target (refer to figure ## for placement of alignment plate)
- Tighten down everything so that it does not move, remove the alignment plate and place the light eliminating box of science (aka a cardboard box) over the photodetector arm. This box eliminates ambient light from interacting with the detector, resulting in clearer readings.

- Record the voltage reading on the multimeter in an excel spread sheet
- Repeat steps 3-5 until the end of the determined range of incident angles is reached
- Repeat this process at least two times per sample to evaluate reproducibility

A. *Measuring Film Thickness*

Atomic force microscopy (AFM) was used to estimate the thickness of the gold films deposited from the Cressington 108-Auto sputter coater. AFM is a method for gathering accurate topography data of samples with surface feature sizes on the nanoscale, as shown in figure ##.

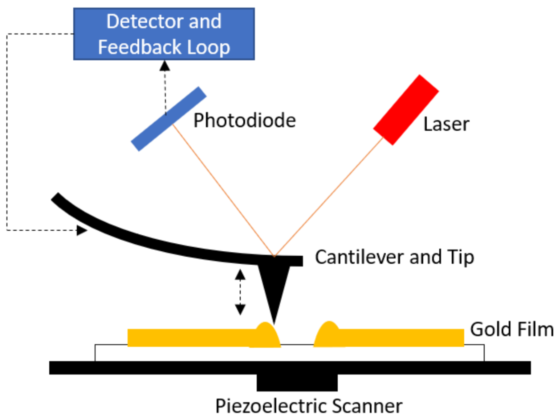


Figure 2.3: Illustration of atomic force microscopy and how it is used to measure the gold film thickness

We decided to use this microscopy technique to quantitatively measure the difference in height between the glass surface and top of gold film. Two methods were used to create a measurable "step" in the gold film. The first method is similar to that used for preparing samples by sputter coating in section B.1. The difference here is before sputter coating a cover slip was taped to the slide to mask a section of the slide from gold deposition. Three samples of different thicknesses were prepared from 2 cycles, 6 cycles, and 10 cycles. When the cover slip is removed, there is a distinct separation of the glass section from the gold film. The other method for creating a height differential required removal of a section of the gold after deposition. This was done by lightly scraping the surface with the edge of a piece of paper. The paper was used to avoid scratching the glass surface which would skew the results to suggest thicker films.

Good images were obtained using the following scanning control settings on the Bruker Innova AFM:

Samples	512
Lines	512
Scan Rate	0.50000 Hz
Scan Range	10.0000 microns

The X and Y offsets were used to make fine adjustments in the position of the cantilever so that the gold "ledge" appeared near the center of the scan range. Gwyddion, an open source image processing program, was used to analyze the AFM images using the following procedure:

- Level data using '**level data to make facets point upward**' option
- '**Extract Profiles**'
- Make a line parallel to the film step on either side of the step, placing it in an area close to the step but avoiding the inclusion of large bumps
- Select '**Apply**'. Another window will open with the extracted profiles
- Right click on the graph and select '**export text**' to export the data to a CSV for data processing

B. *Calculating Index of Refraction of Gold*

To calculate the index of refraction of gold, you need to find the critical angle, then you can use equation 1.5 to solve for n_t. Like the other methods, the actual angle measured is at the air to glass interface. Then using equation 1.4 the critical angle can be calculated. To measure the air to glass angle we set up a HeNe laser to be perpendicular to one of the prisms legs. To determine if the prism is perpendicular we checked the back reflection of the laser on a piece of paper with a small hole in it. When the reflected beam is centered on the hole in the paper the laser is perpendicular to the face of prism. After this, simply rotated the prism on the beam until the transmitted beam disappeared. By recording the reading of our rotatable dial before and after we get a change in incident angle that can then be converted to the critical angle and finally the index of refraction of gold like stated above.

III. Results

A. Thin film type and effect on resonance curve

The reflectivity is the ratio of reflected light to incident light and is plotted in figure ##. There are three effects that result from changing the metal used for the thin film. First, with the gold we see a wider range of incident angles which result in decreased reflectivity than compared to the silver film. This matches what we visually see when running our experiments because the darker band where resonance is occurring is wider for the gold film and thinner for the silver film. Second, the angle at which peak resonance occurs is different for gold and silver. The gold film has a measured peak resonance at an incident angle of about 45 degrees and the silver at 43 degrees. These results agree with what was stated in the introduction, that Θ_{SPR} is dependent of the refractive index of the metal film. Third, the difference in maximum reflectivity and minimum reflectivity for gold is greater than silver. There are couple possible explanations for this. The optimal film thickness for resonance could be different for gold and silver or the area of resonance for silver is so thin that the detector is picking up extra light from the sides of the band.

Figure 3.1: Graph of Θ_{SPR} vs average reflectivity for a 50 nm thick silver film and a. approximately 50 nm thick gold film.

B. *Estimated film thickness from AFM analysis*

The height profiles collected from the processed AFM images were exported to Excel and analyzed. For films coated 2 times, the average thickness was 25 nm, suggesting each cycle deposits a 12.7 nm layer of gold particles. The films coated 6 times had an average thickness of 49 nm. The variability for these films was quite high, as shown by the high relative standard deviation. This results in an estimated 8 nm layer formed after each cycle. The samples coated 10 times averaged 98 nm thick, which is approximately 9.8 nm of gold deposited after each cycle. Since the standard deviation is lowest for the film coated 10 times, it is reasonable to conclude that the actual deposition thickness from each cycle is somewhere slightly above 9.8 nm. Assuming a 9.8 nm layer of gold is deposited after each cycle, the thickness of the 6x coated films is 58.8 nm and the 2x coated film is 19.6 nm.

Sample #	**Average (nm)**
#1 Coated 10x	97.71081±1.099291
#2 Coated 10x	97.69248±1.621665
#3 Coated 10x	97.47499±5.802606
Total Average:	97.62609±0.0655893
#1 Coated 6x	42.18372±3.074965
#2 Coated 6x	45.84373±3.275026
#3 Coated 6x	54.57454±1.210458
#4 Coated 6x	56.90059±0.9867052
Total Average:	49.87564±3.498232

#1 Coated 2x	19.52943±1.051858
#2 Coated 2x	27.00225±0.6785435
#3 Coated 2x	28.29600±6.684253
#4 Coated 2x	26.81636±1.646727
Total Average:	25.41101±1.721612

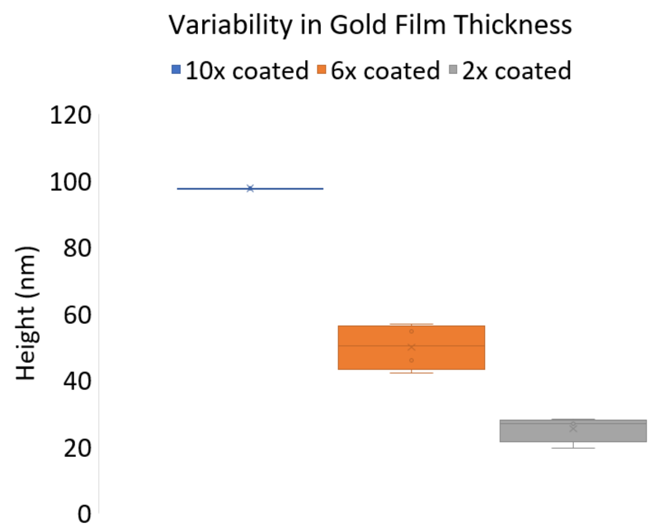


Figure 3.2: (left) Table of values collected on the gold film thickness using atomic force microscopy. (right) Boxplot showing variability of measured thicknesses. The filled area represents the standard deviation, the mean value is marked with an 'x', and the 'whiskers' indicate the max and min values.

When collecting AFM images, there was a recurring artifact that appeared which is shown in figure ##. This somewhat triangular looking artifact occurs repeatedly across the whole scan. When the cantilever tip is switched out, the artifact disappears. Therefore, the conclusion is that this anomaly is caused by a contaminated tip.

It has been shown in other papers that very defined resonance will occur at film thicknesses around 60 nm. This suggests that the curves collected for 6x coated samples should be the most defined because they are the closest to 60 nm by our estimation. This will be evaluated in the next section.

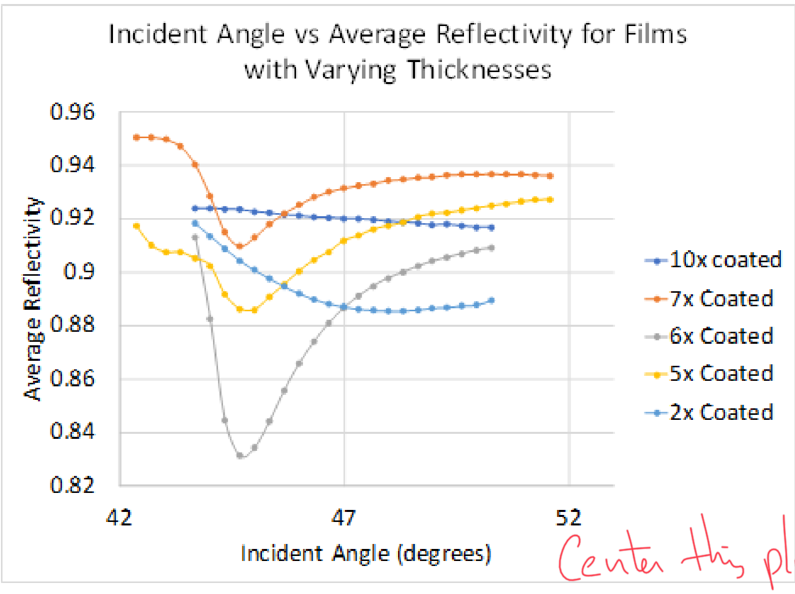
C. *Effect of thin film thickness on resonance intensity*

Using the estimation from section B, the film thicknesses used in this experiment are:

Times coated	Film Thickness (nm)
2	19.6
5	49
6	58.8
7	68.6
10	98.0

The data plotted in figure ## suggests the thickness that leads to the most pronounced drop in intensity, is 58.8 nm. The other two films closest to this thickness still showed a drop in intensity and at a similar incident angle to the 58.8 nm thick film but the magnitude of the drop is not as large. The 19.6 nm thick film and 98.0 nm thick film did not show a point of resonance. These trends agree with what has been reported in literature. If the film is too thin, then total internal reflection will not occur because the difference in refractive indices is not high enough and transmission of the incident light will continue. If the film is too thick, the evanescent wave decays before it can interact with the surface plasmon and so resonance will not occur.

Try to give this plot more discussion. This is beautiful data and shows fairly conclusively that this is surface plasmon resonance.



Center this plot

Figure 3.3: Connected scatterplot of gold-glass incident angle versus the average reflectivity for gold films of different thicknesses.

A couple of drawbacks to the sputter coater method should be mentioned. The thickness of gold film on the slides that we prepared they can vary due to the sputter coater not applying the gold in an even coating. This can lead to flaws because as the prism rotates, the incident light is hitting different spots on the film and, as shown, the thickness of the film influences how intense the reflected light is. In addition, during our time using the sputter coater, the gold film source material was very worn with holes in it. The gold ions coming off the source material could be polydisperse in size and more concentrated in certain areas leading to ununiform films. This may have led to deviations in our data.

D. *Iris opening diameter and effect on resonance for silver and gold films*

Of the three iris diameters, the 1.25 mm diameter led to the largest drop in average reflectivity for both the gold and silver films. When the iris opening was 5.00 mm or larger, the drop in reflectivity was much smaller. Our thought is that this is because the photodiode is picking up the reflected light around the area of resonance when the iris opening is larger than the area of resonance. Our experiment for the gold film suggests the width of the resonance band is less than 1.25 mm. Therefore, using a smaller beam of light allows to more accurately measure the actual drop in reflectivity.

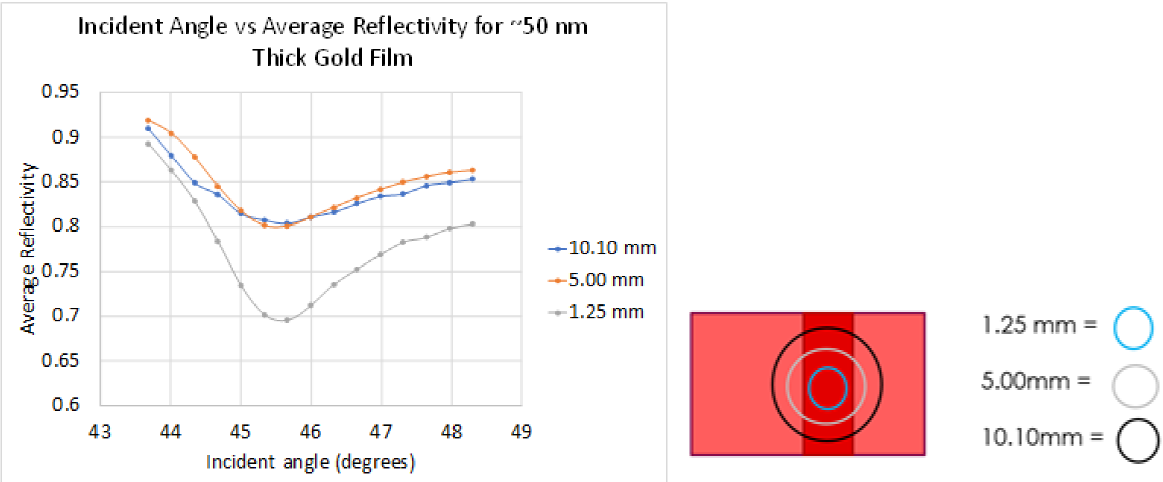


Figure 3.4: (Left) Connected scatterplot of the glass-gold incident angle versus the average reflectivity of an approximately 50 nm thick gold film when the diameter of the iris is set to a specific value. (Right) Graphic showing how reflectivity is impacted by iris size.

	1.25 mm Iris Diameter	5.00 mm Iris Diameter	10.10 mm Iris Diameter
~50 nm Gold film Reflected Light Intensity (mV)	42.84	33.89	34.34
50 nm Silver film Reflected Light Intensity (mV)	22.91	14.91	6.73

Figure 3.5: Table showing the difference between the maximum and minimum recorded reflected light intensities for gold and silver films.

IV. Discussion

The researchers involved in this project were interested in learning how surface plasmon resonance can be used to characterize thin films. To answer this question, it is important to understand how varying thin film characteristics alters the resulting SPR curves. Once the variables and their effects are quantified, this technology can be used to fabricate sensors that detect changes in environments.

The angle optimal for resonance (θ_{SPR}) must be above the critical angle for total internal reflection[5] depicted in equation 1.5. Total internal reflection is needed in order for the evanescent wave to propagate along the surface of the gold. Given the index refraction of the prism (THOR LABS right angle prism N-BK7)[6] to be 1.515 and the index of refraction of gold to be 1.137 the critical angle for the glass to gold interface is 48.63 degrees. The critical angle for the glass to gold interface can also be calculated using Fresnel's equations given the indices of refraction. This critical angle is where the reflected power approaches 1.0, which for glass and gold it is 48.63 degrees. Knowing this critical angle, we would expect surface plasmon resonance to occur at an angle greater than 48.63 degrees. However, our data shows that on average resonance occurs at 44.78 degrees, as shown in figure ##, for films with thicknesses between 40 and 60 nm. The 20 nm and 100 nm film were ignored due to resonance not occurring. This discrepancy is most likely due to the accuracy of calculating the index of refraction of the gold film described in Materials and Methods section D. The uncertainty, if calculated would be large enough to include indices of gold that would produce an angle below 44.78 degrees, thus matching the statement of having the resonance angle above the critical angle. This calculation can be improved upon by experimentally obtaining a more accurate angle of resonance.

The experiments and results described in this paper show the effects of multiple variables on surface plasmon resonance. Changing the thin film material causes a shift in the incident angle for plasmon resonance as well as differences in resonance magnitudes. Since the incident angle vs reflectivity curves will change based on the material used, future work could be done on other types of metal films.

Resonance will occur for gold films with thicknesses greater than 20 nm and less than 100 nm, with the greatest drop in reflectivity occurring with 60 nm thick films. This conclusion agrees with statements made in literature explaining surface plasmon resonance. A connection between film thickness and calculated refractive index for gold could be pursued by future researchers. In general, if other variables are to be evaluated, researchers should plan their experiments around using one thickness of film, around 60 nm.

When using un-collimated light, the resonance band can be seen easier. However, if un-collimated light is used to measure intensity with changing incident angles, it is important to limit the size of the incident beam. This width of the beam can be changed by opening or closing an iris. The diameter of the iris should be smaller than the width of the resonance band to get an accurate reading for drop in reflectivity.

In addition, Raman spectroscopy paired with SPR is another path that could be pursued. Future researchers could consider introducing additional molecules, in gas or liquid phase, to the film surface and measuring the effect this has on the resonance curve.

References

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