Surface Plasmons

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A new experimental setup was established and calibrated for surface plasmon measurement. Using this setup, an optical method is described to measure the dispersion relationship of surface plasmon waves (SPW) in a thin film of silver. SPW was excited optically by the evanescent wave present in total reflection for TH polarized light with a special incident angle. The results of these measurements agree with those of previous experiments.

I. Introduction

In this experiment, we use Kretschmann's approach [1] to measure the dispersion relationship of SPW. Upon the total reflection of TH polarized incident light from the glass and air interface in a prism, surface plasmon waves can be excited in a silver thin film locating right at the interface, and its wave vector can be determined by finding the minimum reflectivity point while the light incident angle is varied.

II. Theory

Considering the electromagnetic wave propagating in free electron metals, it is well known that, at some certain frequency, the metal can become transparent to the radiation of that frequency. This frequency is called plasma frequency. Another important consequence of this effect is that the electron gas can sustain charge density oscillation, in the form of a longitudinal density wave propagating through the medium. As an extension of this phenomenon, at the interface of a metal and dielectric medium, such as air, Maxwell's theory predicts that a transverse magnetic (TH) electric magnetic wave can propagate along the surface of the metal due to fluctuation of the surface charge density. This is the so-called SPW.

The dispersion relation of SPW can be obtained by solving Maxwell's equation under proper boundary condition, which yields:

$$k_{SP} = \sqrt{\frac{\varepsilon(\omega)\varepsilon_d}{\varepsilon(\omega) + \varepsilon_d}}k_0$$

where k_{sp} and k_0 is the wave vector of surface plasmon and incident light, respectively, $k_0 = \omega/c$. ε_d is the dielectric constant of the dielectric medium. For air, $\varepsilon_d=1$. $\varepsilon(\omega)$ is the complex dielectric constant of the SPW. $\varepsilon(\omega) = \varepsilon_1+i\varepsilon_2$. $\varepsilon_1 = 1-\omega_p^2/\omega^2$ as predicted by Drude theory.

Since the SPW have a nonlinear dispersion relation, meaning its wave vector is always larger than the wave vector of the incoming photon, the SPW can not be directly excited by shining light onto the surface of the metal.

In 1968, Otto [2] put forward an idea of using total reflection of light in a prism to excite SPW in a metal. In his case, the metal film was put close enough to the interface of the prism surface and air so that evanescent field of light can be sensed by the metal. Because the wave vector of the evanescent wave along the interface direction is

$$k = k_0 n \sin\alpha$$

which can be larger than k_0 when $n\sin\alpha>1$. The SPW can be excited at some certain point where $k=k(\omega)$ as illustrated in Fig 1.

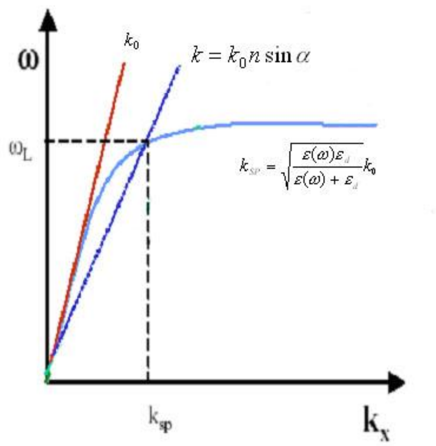

Fig 1. Dispersion relation of SPW, incident light and evanescent wave

However, this experiment is not easy to repeat since it requires a very precise control of the thickness of the air gap, which is on the order of a couple thousand angstrom.

In 1971, Kretschmann [1] demonstrated a modified Otto geometry. The metal film was put in between the dielectric layer and air, and kept thin enough so that the concept of total reflection at the interface was still working, while the experimental setup was less requiring.

III. Experiment

a. Apparatus

The experimental setup for SPW measurement is shown in Fig.2. The light output from a broad band light source passed through a monochomator for wavelength selection. Then the light was polarized and collimated by the polarizer and collimator, respectively. The silver thin film to be measured was deposited on glass substrate and attached to one of the right angle side of the prism with the glass side facing the prism. Mineral oil was used as the adhesive. On another glass slide that is attached the other right-angle side of the prism, a thick film of aluminum was deposited just to enhance the total amount of light being reflected to silver film. This time, the metal film side was facing the prism. The prism was mounted on a rotatable spectrometer table so that the orientation of the prism can be carefully measured. Finally, the light coming out of the prism was reflected by a mirror and collected by a photometer to measurement the light intensity.

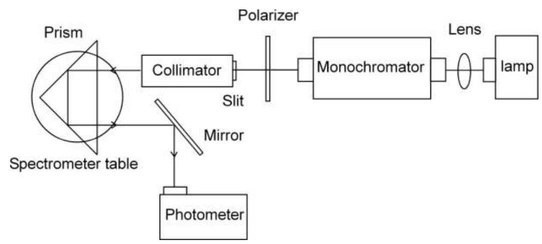

Fig. 2. Schematics of experimental setup for surface plasmon measurement

1. Lamp - Oriel Corp., tungsten bulb, 120W, wide-band light source.
2. Monochromator - Jarrel-Ash model 82-410, high blaze grating, for wavelength selection
3. Polarizer – select TH or TE light polarization
4. Slit – adjustable, for beam shaping and intensity variation
5. Collimator – collimate the beam after passing through the slit
6. Glass prism – where incident light will be total reflected at the sample

7. Spectrometer table – for precise angular dependent measurement
8. Mirror – to reflect the light into photometer
9. Photometer – solid-state detector, OPTEC, Inc., model SSP-3

b. Upgraded components

In this experimental setup, a couple of components have been upgraded so that better system performance can be expected. The new lamp is much more powerful than before. The maximum power of the tungsten bulb inside is 120W. For longer wavelength range (>500nm), about 60W (8A) power would be quite enough to get a strong signal. For the shorter wavelength (<500nm), the power can be increased to maintain the signal to noise ratio. The monochromator is also new. The wavelength tuning knob of this new unit is a big improvement compared to the old one. High precision control allows sub-nm accuracy wavelength selection. There are two dispersion gratings available inside the monochromator. One with high blaze wavelength ~ 600nm, another with low blaze wavelength ~300nm. Both gratings have groove density of 1180 groove/mm. The monochromator has a linear dispersion of 3.3nm/mm. The slits mounted at the entrance and exit of the monochromator were made in the machine shop. The surface of the slit was anodized to minimize unwanted light scattering and reflection. We have two sets of slits, with 0.32mm and 0.5mm slit width, respectively. Considering the linear dispersion of the monochromator, this means spectral purity these two slits can produce are 1.06nm and 1.65nm. Holders for the monochromator and spectrometer table were also ordered from the machine shop. They are specially designed for better stability and at the same time, offering flexibility for alignment if necessary. The height of the lamp and monochromator is adjustable. They should be on the same level as the collimator. The mount for the spectrometer table is fixed to the underneath base by three screws. The orientation of the collimator can be precisely aligned to the output slit of the monochromator by loosing these screws and rotate the mount by hand.

c. Monochromator calibration

The monochromator was calibrated before use. A mercury lamp was mounted at the entrance slit of the monochromator as the light source. For better accuracy, the narrowest slits (0.32mm) were used for the monochromator. The calibration was only performed for high blaze grating.

Spectral line (nm)	Reading (nm)
435.8	436.0
546.0	546.0
871.6	873.0

As can be seen from the table above, the monochromator is well calibrated in the wavelength range of interest.

d. Metal film preparation

The silver and aluminum film were prepared in Edwards Vacuum Evaporator. They were deposited on ~1mm thick glass substrate. The surface of the glass needs to be very clean for good measurement results. The deposition rate were kept relatively low (1~2 angstrom/sec) so that the deposited film could be more uniform. The thickness of the silver film is ~400 angstrom. It looks almost semitransparent. The aluminum film was thicker, ~800 angstrom, for a better mirror effect. The finished films were kept in a desiccator before usage, to slow down the oxidation and degradation.

e. Measurement of the index of refraction of the prism

The index of refraction of the prism was measured by the minimum angle deviation method.

- ❖ Take the prism off the spectrometer table. Use the telescope on the spectrometer table to find the angle of incident light from the output of the monochromator.
- ❖ Set the monochromator at desired wavelength.
- ❖ Put the prism back on. Rotate the prism table and find the minimum angle deviation position with the help of the telescope.
- ❖ Read the angle and find the angle between the incident light and outgoing light.

For minimum angle deviation, δ_m, the angles of light entering and exiting the prism will be symmetric, as shown in Fig. 3.

Recall Snell's Law: $\frac{n_{prism}}{n_{air}} = \frac{\sin\theta_1}{\sin\theta_2}$

By simple geometry, $\theta_2 = \frac{\alpha}{2}$ and the deviation $\delta_m = 2\theta_1 - \alpha$.

From these, the index of refraction of the prism can be calculated:

$$n_{prism} \cong \frac{\sin\left(\frac{\delta_m + \alpha}{2}\right)}{\sin\left(\frac{\alpha}{2}\right)}, \alpha = \frac{\pi}{4}$$

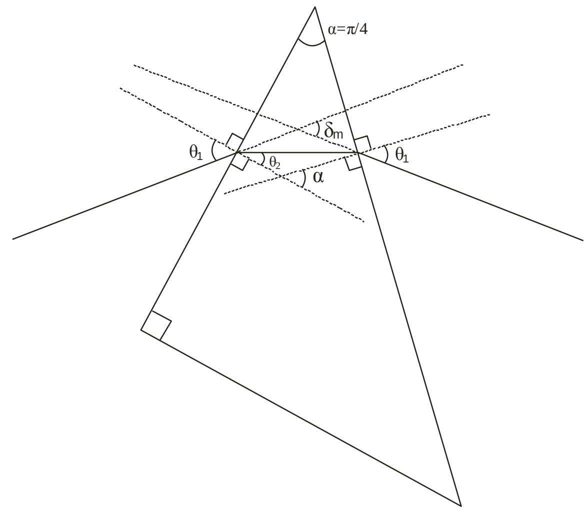

Fig.3. Diagram for measurement of index refraction of the prism by minimum deviation angle method.

f. Measurement of the SPW dispersion relation

To measure the SPW dispersion relation, we need to find both ω and k of the SPW. The SPW share the same frequency as the photons, so ω can be easily calculated from the wavelength settings on the monochromator.

$$\omega = 2\pi c / \lambda$$

At any given wavelength, the wave vector number of the SPW can be calculated by

$$k_{SP}(\omega) = n\ k_0 \sin\alpha$$

where n is the index refraction of the prism and α is the light incident angle at the total reflection of silver sample as illustrated in Fig.4.

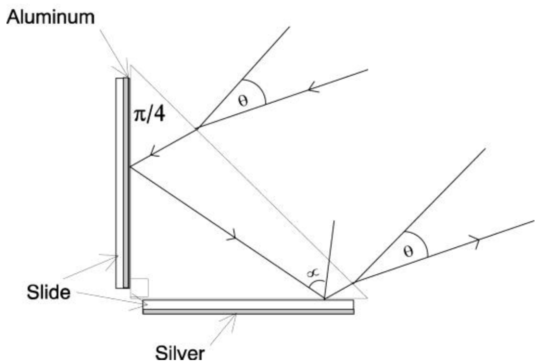

Fig 4. Diagram of light propagation path through the prism.

Once angle θ is measured, α can be calculated by

$$\alpha = \frac{\pi}{4} - \arcsin\left(\frac{\sin\theta}{n}\right).$$

The experiment steps are as follows:

- Attach the silver and aluminum glass slides to the prism as shown in the figure above with mineral oil.
- Find the prism orientation reference angle. Fix the scope at the position 90^o off the incoming light (on the opposite side of the photometer). Rotate the prism table until the light reflected from the long edge of the prism exactly go through the center of the scope. This corresponds to the position that $\theta = 45^o$.
- Align the mirror and photometer so that most of the light is being collected. Use the viewfinder on the photometer when doing this. A clear slit image should be seen and correctly centered. Note only the light inside the circle at the center of the viewfinder will be detected.
- Keep the environment as dark as possible. Block the leak-out light from the lamp by aluminum foils, but NOT touching the electrodes. Do Not block the air flow required to cool the lamp
- Set the monochromator at desired wavelength.
- Set the polarizer at TH polarization (90^o)
- Release the prism table, look into the viewfinder and rotate the prism by hand slowly. At some point, the intensity of the light will reduce dramatically.
- Fix the prism table. Look at the reading of the photometer while rotating the actuator of prism table. Find the position where the reading is minimum. This corresponds to the position of SPW resonance peak.
- Collect a few data points in the neighborhood of the resonance peak. Measure both TH and TE polarized light intensity. Background signal data is also taken and subtracted from the signal.

IV. Tasks

a. Measurement the index of refraction

Measure the index of refraction of the prism over the desired rang of wavelengths.

b. Measurement of SPW

Measured SPW at several wavelength points: 400nm, 450nm, 500nm, 550nm, 600nm and 650nm and the intensity ratio of TH/TE as a function of light incident angle

The data should show an easily seen SPW resonance in all wavelengths, especially the longer wavelength.

The SPW dispersion relation can be obtained by plotting the incoming photon energy against light incident angle at the total reflection.

V. Acknowledgements

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2)Otto, A. Exitation of nonradiative surface plasma waves in silver by the method of frustrated tota reflection. Z. Phys. **216,** 398 (1968).
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