



**UNIVERSITI PUTRA MALAYSIA**

**OPTICAL PERMITTIVITY OF ALIPHATIC ALCOHOLS, POLYETHYLENE  
GLYCOLS AND DYE SOLUTIONS USING THE SURFACE PLASMON  
RESONANCE TECHNIQUE**

**NURUL IZRINI BINTI IKHSAN**

**FS 2009 14**

**OPTICAL PERMITTIVITY OF ALIPHATIC ALCOHOLS, POLYETHYLENE  
GLYCOLS AND DYE SOLUTIONS USING THE SURFACE PLASMON  
RESONANCE TECHNIQUE**

**By**

**NURUL IZRINI BINTI IKHSAN**

**Thesis submitted to the School of Graduate Studies, Universiti Putra Malaysia,  
in Fulfillment of the Requirements for the Degree of Master of Science**

**April 2009**



***Specially Dedicated to:***

**My beloved parents;**  
*Ikhsan B. Sarpin & Esah Bt Ahmad*  
For their love, support and concern....

**My dearest fiancé;**  
*Amir Hafiz Izzudin B. Amir Sharifuddin*  
For his love, understanding, patience and care...

**My Bro' and Sis' in-law;**  
*Mohd Darul Idzuar & Zaliha*

**My cutely niece & nephew;**  
*Nurdzania Batrisyia & Syahmi Haiman*

**My supervisor;**  
*Prof. Dr. W. Mahmood Mat Yunus*  
For his encouragement, guidance and advice...

**And all my friends...**



Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Master of Science

**OPTICAL PERMITTIVITY OF ALIPHATIC ALCOHOLS, POLYETHYLENE GLYCOLS AND DYE SOLUTIONS USING THE SURFACE PLASMON RESONANCE TECHNIQUE**

By

**NURUL IZRINI IKHSAN**

**April 2009**

**Chairman : Professor W. Mahmood Mat Yunus, PhD**

**Faculty : Science**

Surface plasmon is a charge density wave that occurs at an interface between a thin metal film and dielectric medium. The most common means of excitation surface plasmon resonance is achieved through the Kretschmann configuration by utilizing the attenuated total reflection (ATR).

In this study, gold with purity 99.99% was deposited onto glass cover slip in a form of thin film (thickness ~ 50 nm) using sputtering technique which then coupled onto one surface of 60° prism using index matching oil. Liquid samples used as the dielectric medium were aliphatic alcohols; (methanol, ethanol and 1-propanol), polyethylene glycols (PEG) series; (PEG 400, PEG 4000, PEG 10000 and PEG 20000) and dye solutions; (methylene blue, rhodamine B and rhodamine 6G). The intensity of the optical



reflectivity was measured as a function of incident angle at the metal and dielectric interface.

The determination of the dielectric constant  $\varepsilon_r$  and  $\varepsilon_i$  for metal and liquid was carried out by fitting the experimental data to the theory using Fresnel Equation. It was found that the permittivity values of  $\varepsilon_r$  and  $\varepsilon_i$  for aliphatic alcohol, polyethylene glycols and dye solutions are linearly proportional to the concentration. The value of the real part of dielectric constant,  $\varepsilon_r$ , is in the range of 1.767 to 1.811 while the imaginary part,  $\varepsilon_i$  is in the range of  $2 \times 10^{-4}$  to  $6 \times 10^{-2}$ .

In the case of resonance angle shift, the resonance angle increased with the increasing of the concentration. The shift in resonance angle ( $\Delta\theta$ ) varies linearly with the concentration. Since the straight line passes through the origin, it is possible to use SPR technique for the detection of aliphatic alcohols, polyethylene glycols and dyes at very low concentration. The slopes of the straight lines represented the sensitivity of the detection. The large value of sensor sensitivity of  $452.763^\circ/(\text{mol/L})$  is obtained for the methylene blue sample.

The kinetic behaviour of the system was also investigated by examining the self-assembling process on the metal surface in real time. The shift in resonance angle increased rapidly with time due to the immobilization of the molecules deposited on the gold thin film surface. For aliphatic alcohol solution at concentration of 0.100 mol/L, ethanol achieved a plateau region faster as compared to methanol and 1-propanol. For



PEG samples at a concentration of 5.5 %w/w, PEG 400 responded faster as compared to PEG 4000, PEG 10000 and PEG 20000 while for dye sample at concentration of 0.010 mol/L, rhodamine 6G responded faster as compared to both rhodamine B and methylene blue.

The experimental results of surface plasmon resonance show that the optical properties and the kinetic behaviour can be determined by using the surface plasmon resonance phenomenon. This work shows that this technique can be a good chemical optical sensor where is suitable to study molecule-dielectric interaction for aliphatic alcohols, polyethylene glycols series and dye solutions in water.



Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Master Sains

**PERMITIVITI OPTIK TERHADAP LARUTAN ALKOHOL ALIFATIK ,  
POLIETILENA GLIKOL DAN BAHAN PEWARNA MENGGUNAKAN  
TEKNIK RESONANS PLASMON PERMUKAAN**

Oleh

**NURUL IZRINI IKHSAN**

**April 2009**

**Pengerusi : Professor W. Mahmood Mat Yunus, PhD**

**Fakulti : Sains**

Plasmon permukaan ialah gelombang ketumpatan caj yang berlaku pada permukaan di antara filem tipis logam dan medium dielektrik. Cara yang paling biasa bagi merangsang resonans plasmon permukaan boleh dicapai melalui konfigurasi Kretschmann dengan menggunakan pengecilan pantulan dalaman penuh (ATR)

Dalam kajian ini, emas dengan ketulenan 99.99% telah disapukan di atas slip kaca dalam bentuk filem tipis (ketebalan ~50 nm) menggunakan teknik percikan, di mana kemudian dilekatkan kepada satu permukaan prisma 60° dengan menggunakan minyak indeks sepadan. Sampel cecair yang digunakan sebagai medium dielektrik ialah alkohol alifatik; (metanol, etanol dan 1-propanol), siri polietilena glikol (PEG); (PEG 400, PEG 4000, PEG 10000 dan PEG 20000) dan larutan bahan pewarna (metilin biru, rodamin B dan rodamin 6G. Eksperimen telah dilakukan dengan mengukur keamatan keterpantulan

optik sebagai satu fungsi kepada sudut tuju pada permukaan logam dan dielektrik. Penentuan pemalar dielektrik  $\epsilon_r$  dan  $\epsilon_i$  bagi logam dan cecair telah dilakukan dengan memadankan data eksperimen kepada teori menggunakan persamaan Fresnel. Didapati bahawa nilai permitiviti  $\epsilon_r$  dan  $\epsilon_i$  bagi larutan alkohol alifatik, polietilena glikol dan bahan pewarna adalah berkadar terus kepada kepekatan. Nilai bahagian nyata bagi pemalar dielektrik  $\epsilon_r$  adalah di dalam julat 1.767 ke 1.811 manakala bagi bahagian khayal  $\epsilon_i$  adalah di dalam julat  $2 \times 10^{-4}$  ke  $6 \times 10^{-2}$ .

Dalam kes anjakan sudut resonans, sudut resonans meningkat dengan pertambahan kepekatan. Anjakan sudut resonans ( $\Delta\theta$ ) berubah secara linear dengan kepekatan. Oleh kerana garis lurus melalui asalan, teknik SPR ini boleh digunakan untuk mengesan alifatik alkohol, polietilena glikol dan bahan pewarna pada kepekatan yang sangat rendah. Kecerunan pada garis lurus mewakili kepekaan pengesanan. Kepekaan pengesan tertinggi adalah pada  $452.76^\circ/(\text{mol/L})$  telah diperolehi pada sample metilin biru.

Perlakuan kinetik sistem juga telah diperiksa dengan memerhatikan proses berkumpul sendiri pada permukaan logam dalam masa nyata. Anjakan sudut resonans meningkat secara mendadak dengan masa yang mana berkaitan dengan endapan molekul pada permukaan filem tipis emas. Bagi larutan alkohol alifatik pada kepekatan 0.100 mol/L, etanol telah mencapai bahagian dataran tinggi lebih cepat berbanding dengan masing-masing metanol, dan 1-propanol. Bagi sampel-sampel PEG pada kepekatan 5.5 %w/w, PEG 400 bertindak balas lebih cepat berbanding PEG 4000, PEG 10000 dan PEG 20000



manakala untuk sampel bahan pewarna pada kepekatan 0.010 mol/L, rodamin 6G bertindak balas lebih cepat berbanding kedua-dua rodamin B dan metilin biru.

Keputusan eksperimen untuk resonans plasmon permukaan menunjukkan bahawa sifat-sifat optik dan perlakuan kinetik dapat ditentukan menggunakan fenomena plasmon permukaan. Teknik ini telah terbukti boleh dijadikan sebagai pengesan optik kimia yang berkesan yang sesuai untuk mengkaji tindak balas molekul-dielektrik pada larutan alkohol alifatik, polietilena glikol dan bahan pewarna di dalam air.



## ACKNOWLEDGEMENT

*In the name of Allah, Most Gracious, Most Merciful...*

Thank you ALLAH for providing me the strength and patience to complete this project efficiently. First of all, I would like to express my sincere gratitude and thanks especially to my project supervisor, Prof. Dr. W. Mahmood Mat Yunus for his invaluable advice patience and constructive criticism during the preparation of this master research project. Without his persistent assistance and exceptional generosity, this work would not have been possible.

I wish to acknowledge my indebtedness to Assoc. Prof. Dr. Zainal Abidin Talib and Assoc. Prof. Dr. Zaidan Abdul Wahab as my co-supervisors for their concern in my project. Special thanks to Pn. Wan Yusmawati Wan Yusuf for her help and cooperation to complete my work and also the willingness to share her precious experience with me. Credit is also due to all the lecturers and technical staffs in the Department of Physics, Faculty of Science, Universiti Putra Malaysia and my entire friends who have directly or indirectly had offered me a helping hand.

Grateful thanks to my dearest parents and family members who never fail to be there for their attention, loves and prayers and also for their understanding and supports throughout this research project.



## TABLE OF CONTENTS

	<b>Page</b>
<b>ABSTRACT</b>	i
<b>ABSTRAK</b>	iv
<b>ACKNOWLEDGEMENT</b>	vii
<b>APPROVAL</b>	viii
<b>DECLARATION</b>	x
<b>LIST OF TABLES</b>	xiv
<b>FIGURE CAPTIONS</b>	xiv
<b>LIST OF ABBREVIATIONS</b>	xix
<b>CHAPTER</b>	
<b>1. INTRODUCTION</b>	
1.1 Surface Plasmon Resonance	2
1.1.1 Attenuated Total Reflection	2
1.1.2 Surface Plasmons	2
1.1.3 Momentum Resonance	3
1.1.4 Evanescent Wave	4
1.1.5 SPR Dependencies	5
1.2 Sample Background	
1.2.1 Aliphatic Alcohols	6
1.2.2 Polyethylene Glycol Series	7
1.2.3 Dye Solution	8
1.3 Advantages From the Surface Plasmon Resonance Study	9
1.4 Application of Surface Plasmon Resonance	9
1.5 Objective of the Research	10
1.6 Outline of the Thesis	11
<b>2. LITERATURE REVIEW</b>	
2.1.1 Detection Characteristics of Surface Plasmon Resonance Technique	12
2.2 Surface Plasmon Resonance as an Optical Sensor	14
2.3 Metal Surface	16
2.4 Vapour as a Dielectric Medium	18
<b>3. THEORY</b>	
3.1 Surface Plasmon Resonance	20
3.2 Surface Electromagnetic Waves	21
3.3 Scattering Linkage of Surface Plasmon Resonance	24
3.4 Angle Dependence of the Reflectivity of Surface Plasmon resonance	27



3.5	Excitation of Surface Plasmons Using Prism Coupling	29
3.5.1	Kretschmann Configuration	29
3.5.2	Otto Configuration	30
<b>4.</b>	<b>METHODOLOGY</b>	
4.1	Sample Preparation	32
4.2	Substrate Cleaning	32
4.3	Thin Metal Film Preparation	33
4.4	Sample Preparation	33
4.4.1	Aliphatic Alcohol Solutions	34
4.4.2	Polyethylene Glycol (PEG) Solution	34
4.4.3	Dye Solution	35
4.5	Experimental Setup	35
4.5.1	Sample Cell	36
4.6	Experimental Procedure	37
4.7	Fitting Experimental Data to the Theoretical Data	38
<b>5.</b>	<b>RESULTS AND DISCUSSION</b>	
5.1	Introduction	39
5.2	Stability of Gold Surface as the Active Layer for Surface Plasmon Technique	39
5.3	Effect of Gold Thin Film Thickness	43
5.4	Measurement of Optical Constant, $\epsilon_r$ , and $\epsilon_i$ of Dielectric Medium	48
5.4.1	Introduction	48
5.4.2	Aliphatic Alcohol	50
5.4.3	Polyethylene Glycol	54
5.4.4	Dye	60
5.5	Sensitivity of Surface Plasmon Resonance	65
5.5.1	Aliphatic Alcohol	65
5.5.2	Polyethylene Glycol	68
5.5.3	Dye	70
5.6	Kinetic Behaviour of Self-Assembly	73
5.6.1	Aliphatic Alcohol	74
5.6.2	Polyethylene Glycol	81
5.6.3	Dye	88
<b>6.</b>	<b>CONCLUSION</b>	
6.1	Conclusion	96
6.2	Suggestion	99
	<b>REFERENCES</b>	100
	<b>APPENDIX</b>	104
	<b>BIODATA OF STUDENT</b>	118
	<b>LIST OF PUBLICATIONS</b>	119



## LIST OF TABLE

TABLE		PAGE
5.1	List of optical properties $\epsilon_r$ and $\epsilon_i$ for aliphatic alcohol at concentration of 0.06 mol/L	51
5.2	List of optical properties $\epsilon_r$ and $\epsilon_i$ for PEG 400, PEG 4000, PEG 1000 and PEG 20000 at concentration of 3.5 %w/w	57
5.2	List of optical properties $\epsilon_r$ and $\epsilon_i$ for dye at concentration of 0.006 mol/L	62

## FIGURE CAPTIONS

FIGURE		PAGE
3.1	Surface electromagnetic wave at the interface with dielectric function of $\epsilon_1$ and $\epsilon_2$	22
3.2	Kretschmann configuration for excitation of surface plasmon resonance, dielectric constants and film thickness.	28
3.3	Kretschmann geometry of the attenuated total reflection (ATR) method	30
3.4	Otto geometry of the attenuated total reflection (ATR) method	31
4.1	Experimental setup for Surface Plasmon Resonance Technique	36
4.2	The construction of the cell in Surface Plasmon Resonance Measurement	37
5.1	The variation of surface plasmon resonance curve for gold exposed only to air from day 1 to day 10	41



5.2	The fitting line for experimental data of gold (dot) as compared to the theoretical (line) graph	41
5.3	The dielectric constant as a function of time for gold sample	42
5.4	The Reflectance as a function of incidence angle for different thickness of gold films	44
5.5	The SPR angle $\theta_{\text{spr}}$ as a function of gold film thickness	45
5.6	The minimum reflectance values as a function of gold film thickness	45
5.6	The variation of dielectric constant, $\epsilon_r$ and $\epsilon_i$ with the thickness of gold film	47
5.7	The reflectivity versus incidence angle for distilled water. The solid line represents the theoretical curve.	49
5.8	The reflectance curve for distilled water, ethanol, methanol and 1-propanol at 0.06 mol/L	51
5.10	The reflectivity versus incidence angle for prism/gold/methanol combination. Solid line is the theoretical curve.	52
5.11	The real part of dielectric constant, $\epsilon_r$ as a function of aliphatic alcohols concentration.	53
5.12	The imaginary part of dielectric constant, $\epsilon_i$ as a function of aliphatic alcohols concentration	54
5.13	Resonance curves for gold/air, gold/distilled water and gold/PEG solution	55
5.14	Reflectance curve for distilled water PEG 400, PEG 4000, PEG 10000 and PEG 20000 at 3.5 %w/w	56
5.15	The reflectivity versus incidence angle for prism/gold/ PEG 400 combination. The solid line represents the theoretical curve.	58
5.16	The real part of dielectric constant, $\epsilon_r$ as a function of polyethylene glycol series concentration	58



5.17	The imaginary part of dielectric constant, $\epsilon_i$ as a function of polyethylene glycol series concentration	59
5.18	The resonance curves for gold/air, gold/distilled water and gold/dye solution	60
5.19	Reflectance curve for distilled water rhodamine B, rhodamine 6G and methylene blue at concentration of 0.006 mol/L	61
5.20	The reflectivity versus incidence angle for prism/gold/ Rhodamine B combination. The solid line represents the theoretical curve.	62
5.21	The real part of dielectric constant, $\epsilon_r$ as a function of dye concentration	63
5.22	The imaginary part of dielectric constant, $\epsilon_i$ as a function of dye concentration	64
5.23	Optical reflectance as a function of incidence angle for Methanol at various concentrations	67
5.24	The shift of resonance angle versus concentration for aliphatic alcohols at various concentrations	67
5.25	The optical reflectance as a function of incidence angle for PEG 20000 at various concentrations	69
5.26	The shift of resonance angle versus concentration for polyethylene glycol series at various concentrations	70
5.27	Optical reflectance as a function of incidence angle of methylene blue at various concentrations	71
5.28	The shift of resonance angle versus concentration for dye at various concentrations	72
5.29	The resonance angle of distilled water versus time	74
5.30	The shift of resonance angle versus time for methanol, ethanol and 1- propanol at concentration of 0.100 mol/L	75
5.31	The shift of resonance angle versus time for (a) methanol, (b) ethanol and (c) 1-propanol at four different concentrations	78



5.32	Stretching Coefficient, $\beta$ versus concentration for Methanol, Ethanol and 1-propanol.	79
5.33	Saturated resonance angle, $\Delta\theta_{\infty}$ versus concentration for Methanol, Ethanol and 1-propanol	80
5.34	Time constant, $\tau$ versus concentration for Methanol, Ethanol and 1-propanol	81
5.35	The shift of resonance angle versus time for PEG 400, PEG 4000, PEG 10000 and PEG 20000 at concentration of 5.5%w/w.	82
5.36	The shift of resonance angle versus time for (a) PEG 400, (b) PEG 4000 (c) PEG 10000 and (d) PEG 20000 at three different concentrations	85
5.37	Stretching Coefficient, $\beta$ versus concentration for PEG 400, PEG 4000, PEG 10000 and PEG 20000	86
5.38	Saturation value, $\Delta\theta_{\infty}$ versus concentration for PEG 400, PEG 4000, PEG 10000 and PEG 20000	87
5.39	Time constant, $\tau$ versus concentration for PEG 400, PEG 4000, PEG 10000 and PEG 20000	88
5.40	The shift of resonance angle versus time for methylene blue, rhodamine B and rhodamine 6G at concentration of 0.010 mol/L	89
5.41	The shift of resonance angle versus time for (a) Methylene Blue, (b) Rhodamine 6G and (c) Rhodamine B at three different concentrations	91
5.42	Stretching Coefficient, $\beta$ versus concentration for methylene blue, rhodamine B and rhodamine 6G	93
5.43	Saturation value, $\Delta\theta_{\infty}$ versus concentration for methylene blue, rhodamine B and rhodamine 6G	94
5.44	Time constant, $\tau$ versus concentration for methylene blue, rhodamine B and rhodamine 6G	95





## LIST OF ABBREVIATIONS/NOTATION/GLOSSARY OF TERM

$\theta_i$	Incidence angle
$\theta_{spr}$	Surface Plasmon Resonance angle
$\Delta\theta$	The shift of resonance angle
$\Delta\theta_0$	The initial shift of resonance angle respect to distilled water
$\Delta\theta_\infty$	The saturated resonance angle
$\varepsilon_r$	Real part of dielectric constant
$\varepsilon_i$	Imaginary part of dielectric constant
$\varepsilon_0$	Dielectric constant of prism
$\varepsilon_1$	Dielectric constant of metal film
$\varepsilon_2$	Dielectric constant of dielectric
$I$	Wave field
$\mu$	Magnetic permeability
$n_p$	Refractive index of prism
$n_m$	Refractive index of metal film
$n_0$	Refractive index of dielectric medium
$k_x$	Wavevector component along surface electromagnetic wave
$k_{sp}$	Wavevector of a plasmon
$\kappa_1$	Wavevector in media 1
$\kappa_2$	Wavevector in media 2
$R$	Reflection coefficient
$R_{min}$	Reflectance minimum
$I_0$	Incidence light
$I_r$	Reflected light
$\lambda$	Wavelength
$d$	Thickness



$c$	Concentration
$\tau$	Time constant
$\beta$	Stretching coefficient
ATR	Attenuated total reflection
Au	Gold
Ag	Silver
EO	Ethylene oxide
MEG	Mono ethylene glycol
MWR	Molecular weight relative
PEG	Polyethylene glycol
SPR	Surface plasmon resonance
SPW	Surface plasmon wave
SPs	Surface plasmons
QCM	Quartz Crystal Microbalance
M	Concentration solution
V	Volume of concentration
T	Temperature
Mol/L	Mol per liter
%w/w	Weight percent.



## CHAPTER 1

### INTRODUCTION

During the last two decades, we have remarkable research and development activity intended at the realization of optical sensors for the measurement of chemical and biological entities (Homola *et al.*, 1999). The first optical chemical sensors were based on the measurement of changes in absorption spectrum and were developed for the measurement of CO<sub>2</sub> and O<sub>2</sub> concentration (Brecht and Gauglitz, 1995). A large variety of optical methods have been used in chemical sensors and biosensors including ellipsometry, interferometer (white light interferometer), spectroscopy of guided modes in optical waveguide structures (grating coupler) and surface plasmon resonance. The chosen quantity is determined by measuring the refractive index, absorbance and fluorescence properties of analyte molecules or a chemo-optical transducing medium (Boisde and Harmer, 1996). The potential of surface plasmon resonance (SPR) for characterization of thin films (Pockrand *et al.*, 1978) and monitoring processes at metal interfaces [Gordon and Ernst, 1980] was recognized in the late seventies. In 1982 the use of SPR for gas detection and biosensing was demonstrated by Nylander *et al.* (1982) and Liedberg *et al.* (1983 and 1995). Since then SPR sensing has been receiving continuously growing attention from scientific community. Development of SPR-sensing configurations as well as applications of SPR sensing devices for the measurement of physical, chemical and biological quantities has been described by Homola *et al.* (1999). In this area, SPR as a surface oriented method has shown a vast potential for affinity biosensors and allowing real-time analysis of bio-specific interactions without the use of labeled molecules.



## **1.1 Surface Plasmon Resonance (SPR)**

SPR is an optical phenomenon occurs in thin metal film under condition of attenuated total reflection (ATR). This phenomenon generates a sharp dip in the intensity of the reflected light at a particular angle known as the resonant angle. This resonant angle depends on numerous factors including the refractive index of the medium (refractive index is directly interrelated to the concentration of dissolved material in the medium) close to the non-illuminated side of the thin metal film. By keeping other factors constant, SPR can be used to measure different concentration of molecules in the surface layer of solution in contact with the sensor surface (gold layer).

### **1.1.1 Attenuated Total Reflection**

When a light beam hits a prism, the light bends towards the plane of interface and passing from denser prism to a less denser one. Varying the incidence angle ( $\theta$ ) will change the out coming light until a critical angle is achieved where all the incoming light is reflected within the prism. This is known as attenuated total reflection (ATR).

### **1.1.2 Surface Plasmons**

In most surface plasmon resonance study, gold is used because it gives a SPR signal at suitable combinations of reflectance angle and wavelength. In addition, gold is chemically inert to solutions and solutes typically used in biochemical contexts (Biacore Ab, 1998). When the light is polarized with its electric field in the plane of incidence, the field causes collective oscillation of the electrons in the metal layer where the energy

of the metal surface coincide with the incident photon and the charge density wave . The incident light is absorbed and the energy is transferred to the electrons which converted into surface plasmons. Photon and electron behaviour can only be described when they have either wave or particle properties. In agreement with the quantum theory, a plasmon is the particle name of the electron density waves. Therefore, in an ATR situation when the quantum energy of the photons is right, the photons are converted into plasmons and leaving a 'gap' in the reflected light intensity.

### **1.1.3 Momentum Resonance**

Like all other variation, the photon to plasmon transformation must preserve both momentum and energy in the process. Plasmons have a characteristic momentum defined by factors that include the nature of the conducting film and the properties of the medium on either side of the film. Resonance occurs when the momentum of incoming light is equivalent to the momentum of the plasmons (resonance momentum). The momentum of the photons and plasmons can be described by a vector function with both magnitude and direction. The relative magnitude of the components changes when the angle or wavelength of the incident light changes. However, plasmons are restricted to the plane of the gold film and for SPR it is only the vector component parallel to the surface that matters. Therefore, the energy and the angle of incident light should be right (light is polarized with its electric field in the plane of incidence) to form surface plasmon resonance.

#### 1.1.4 Evanescent Wave

In ATR, the reflected light generates an electric field on the opposite side of the interface. The plasmons create a comparable field that extends into the medium on either side of the film. This field is identified as the evanescent wave because the amplitude of the wave decreases exponentially with increasing distance from the interface surface and decaying over a distance of about one light wavelength (Nagata and Handa, 2000). The depth of the evanescent wave which is useful for measurements is within  $\sim 300$  nm of the sensor surface. The wavelength of the evanescent field wave is the same as that of the incident light. The energy of the evanescent wave is dissipated by heat. The equations which describe how electric fields travel through a medium include a term for the properties of the medium and for light. This term is recognized as the refractive index. The light is seen as refracted because the photons have a different velocity in different media. In the same way, the velocity (and therefore the momentum) of the plasmons is changed when the composition of the medium changes. When the momentum change, the angle of incident light at which the resonance occurs was also changed and known as resonant angle or angular SPR (Markey, 1999) and (Akimoto, 2000). Alternatively, at a fixed angle of incident light, the wavelength can be varied until resonance occurs (Quinn, 2000). This is known as resonant wavelength SPR or spectral SPR and is not widely used (Akimoto, 2000). A full wavelength spectrophotometer can simultaneously observe the wavelength from 400 – 800 nm and is more accurate than angle measurements.