Piezoelectric and Surface Plasmon Resonance Based Optical Elements for Sensing Applications

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International Journal of Engineering & Technology Research
Volume 3, Issue 6, November-December, 2015, pp. 15-19
ISSN Online: 2347-4904, Print: 2347-8292, DOA : 20112015
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ABSTRACT

This paper comprises of study on novel optical thin films which reveals a combination of surface plasmon resonance and piezoelectric effects. The study indicated that inclusion of Ag nanoparticles in piezoelectric material pave the shifting of its prominent peak in the visible spectrum. This optical range is necessary in the proposal of optical elements for sensing systems. These novel optical elements with piezoelectric characteristics can be tunable under well-defined bias and hence opening novel possibilities in the fabrication of further sensitive and multifunctional microdevices.

Keywords: *Piezoelectric Effect, Silver, Surface Plasmon Resonance, Sensor*.

1. INTRODUCTION

The prominence need of have reliable, accurate, efficient and cost effective sensors has been the objective of current researches. Surface Plasmon Resonance (SPR) with immobilized metal nanoparticles in a polymer matrix with suitable combination facilities the observance precisely exact package of optoelectronic, optical and electronic properties. The nanocomposite based plasmonic materials with metal nanoparticles shows very high selectivity for a given material in a combination of materials [1]. This property of SPR sensors were rich utilized in food, medical and bio- industries [2-4].

An another class of sensors; the piezoelectric sensors were of emerging significance in the field of biosensing applications. The piezoelectric ceramic such as lead zirconate titanate (PZT) based sensing element is expected to be of higher sensitivity but being brittle and heavy they are of high acoustic impedance and are not suitable for low frequency sensing applications. However, the piezoelectric polymer such as poly(vinylidene fluoride) (PVDF), and the other ceramic-polymer composites such as PZT-PVDF and $BaTiO_3$-PVDF etc. pave the way for material selection in order to fulfill the need of flexible, sensitive, selective and low acoustic impedance sensors [5].

It is expected that apart from novel properties of materials; surface patterning of sensors propose the possibilities of further addition to the sensing applications field. This paper proposes an analytical study of an optical sensing element consists of piezoelectric material with a periodical patterning over it which exhibits the plasmonic nature. The presence of mixture of specific properties in a single material remarkably impacts the results in sensing applications.

 ISSN (O) 2347-4904
(P) 2347-8292

2. THEORY

The phenomena surface plasmon resonance is achieved by attenuated total internal reflection utilizing Kretschmann's configuration. In this configuration, a high refractive index prism is coated with metal layer touching the unknown sample. In a prism based SPR sensor, light of some fixed wavelength (angular interrogation) is incident at various angles on the metal coating. And at some θ_{SPR} there is transfer of energy of evanescent waves to surface plasmons resulting in a decrease in the reflected light. Presently this high refractive index prism is replaced with an cantilever beam which consists of a PVDF and Ag nanoparticles composite piezoelectric material layer with periodical patterning over it bonded over steel substrate as shown in Fig. 2.1.

In a nanocomposite material, nanoparticles of one component material are embedded in a continuous host dielectric matrix of other component [6]. If the particle sizes of nanoparticles are much smaller than the wavelength of the incident radiation, then without the violation of Rayleigh's scattering theory, the effective dielectric constant of nanocomposite can be determined by using Maxwell-Garnett Model [7].

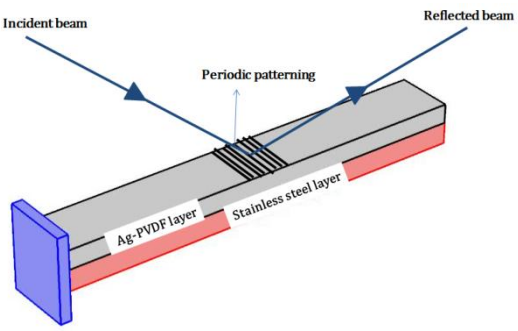

Fig. 2.1 Schematic Diagram of SPR Based Cantilever Sensor with Metal-Piezoelectric Nanocomposite Layer

If ε_1 is the dielectric constant of metal/metal oxide nanoparticles of component 1 and ε_2 is the dielectric constant of host piezoelectric matrix of component 2, the effective dielectric constant of nanocomposite is given as,

$$\varepsilon_{eff} = \varepsilon_2 \left[\frac{\varepsilon_1 + 2\varepsilon_2 + 2f(\varepsilon_1 - \varepsilon_2)}{\varepsilon_1 + 2\varepsilon_2 - f(\varepsilon_1 - \varepsilon_2)} \right] \qquad (2.1)$$

Where, f is the volume filling factor (volume fraction) of nanoparticles of component 1. In the present investigation, Ag is considered as component 1 while PVDF is regarded as component 2.

The dielectric constants of Ag metals are written according to Drude model as,

$$\varepsilon_1 = 1 - \frac{\lambda^2 \lambda_c}{\lambda_p^2 (\lambda_c + i\lambda)} \qquad (2.2)$$

Here, λ_p and λ_c are the plasma wavelength and the collision wavelength of Ag . Where, λ_p = 1.4541 x 10^{-7} m ,and λ_c = 1.7614 x 10^{-5} m [8].

The dielectric constant of host piezoelectric matrix PVDF is written according to Drude model as [9],

$$\varepsilon_2 = \varepsilon_\infty \left[1 + \frac{(\omega_{LO}^2 - \omega_{TO}^2)}{(\omega_{LO}^2 - \omega^2 - i\omega\gamma)} - \frac{\omega_p^2}{(\omega^2 + i\omega\Gamma)} \right] \qquad (2.3)$$

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Here, ε_∞ is the high frequency dielectric constant, ω_{LO} and ω_{TO} are LO and TO frequencies of phonon mode, ω_p is the plasma frequency, γ and Γ are the two corresponding damping constants.

The expression for the reflection coefficient (reflectance) of p-polarized incident light is obtained by using the matrix method for N-layer model as mentioned in appendix A. Considering that all the guided rays are launched over the eam using a collimated source and a microscope objective, the angular power distribution of rays guided is given as [10],

$$dP \propto \frac{n_1^2 \sin\theta \cos\theta}{(1-n_1^2\cos^2\theta)^2} d\theta \qquad (2.4)$$

Where, θ is the angle of the ray with the normal to the beam surface. Also, n_1 is the refractive index of the surrounding medium. To calculate the effective transmitted power, the reflectance (R_p) for a single reflection is raised to the power of the number of reflections the specific propagating angle undergoes with the sensor interface. Hence, for p-polarized light, the generalized expression for the normalized transmitted power in an optical fiber based SPR sensor will be given as,

$$P_{trans} = \frac{\int_{\theta_{cr}}^{\pi/2} R_p^{N_{ref}(\theta)} \frac{n_1^2 \sin\theta\cos\theta}{(1-n_1^2\cos^2\theta)^2} d\theta}{\int_{\theta_{cr}}^{\pi/2} \frac{n_1^2 \sin\theta\cos\theta}{(1-n_1^2\cos^2\theta)^2} d\theta} \qquad (2.5)$$

Where,

$$N_{ref}(\theta) = \frac{L}{D\tan\theta} \qquad (2.6)$$

And,

$$\theta_{cr} = \sin^{-1}\left(\frac{n_{cl}}{n_1}\right) \qquad (2.7)$$

Here, $N_{ref}(\theta)$ is the total number of reflections performed by a ray making an angle θ with the normal to the beam layer. L and D are the length of the exposed sensing region and the fiber core diameter respectively. Also, θ_{cr} is the critical angle at the surface and n_{cl} is the refractive index of the nanocomposite layer of the beam.

3. RESULTS AND DISCUSSION

Figs. 3.1 show the SPR transmittance curves for Au-PVDF nanocomposite layers having thicknesses 50 nm with volume fraction of 0.85

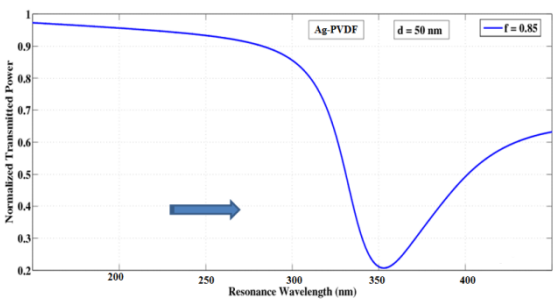

Fig. 3.1 SPR Transmittance Curves for Au-PVDF Nanocomposite Layers Having Thicknesses 50 Nm with Volume Fraction of 0.85

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Being of semicrystalline nature PVDF shows sharp absorbance at 240nm [11], however, remarkable shifting is observed when PVDF is synthesized with silver nanoparticles i.e. precise and controlled peak determination ended up with a sharp peak at 352nm with improved power. This shifting in absorption towards visible spectrum in PVDF based material impinges the consequence of variation in energy band gap and more probably these shifted visible spectrum peaks are SPR peaks corresponds to silver nanoparticles in PVDF polymer matrix [12].

In active optical elements of various sensors the presence of optical window is severely desired and for most of them the active range is in visible region of spectrum. Hence PVDF-Ag nanocomposite which shows a sharp absorption peak in the visible region can be utilized for optical window material.

Effect of Periodicity

Under the effect of an applied electric field along the piezoelectric layer, periodicity over it (i.e. such as reflection grating) stretches its periodic patterning.

It not only influences the orientation of maximum and minima with respect to optical element but also among their mutual intensities.

Using the Euler's Bernoulli beam theory and Bragg's law od diffraction it can be obtained that it's a high efficiency reflection grating that is with excellent contrast among maximum and minimum intensities.

A optical sensing element comprises of piezoelectricity and surface plasmon resonance on same platform is an advantageous device to study the inclusive happening of dynamics and equilibrium processes in the field of molecular biology surface phenomenas associated with biomedicine and pharmacy [11].

4. CONCLUSIONS

Above analytical study reveals that addition of Ag nanoparticles not only shifts the resonance wavelength in visible spectrum but also enhance the absorbance on that. This consideration of these devices can be exploit for beam switching applications such as used as monochromatic light source and for the study of biological laboratory systems.
The higher observed wavelength or low frequency is ambient with the desired frequency associated with human monitoring devices.

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