Sensors and Actuators B 198 (2014) 366–376

Contents lists available at ScienceDirect

Sensors and Actuators B: Chemical

journal homepage: www.elsevier.com/locate/snb

High sensitivity lossy mode resonance sensors

Davinder Kaur [a], V.K. Sharma [b], A. Kapoor [a,*]

[a] Photovoltaics And Opto Electronics Lab, Department of Electronic Science, University of Delhi, South Campus, Benito Juarez Road, New Delhi-110021, India
[b] Keshav Mahavidyalaya, University of Delhi, Delhi-110034, India

ARTICLE INFO

Article history:
Received 21 November 2013
Received in revised form 8 March 2014
Accepted 16 March 2014
Available online 26 March 2014

Keywords:
Thin absorbing films
Lossy modes
Lossy mode resonance
Evanescent wave
Biosensors
Indium tin oxide

ABSTRACT

We propose a sensor based on spectral as well as angular interrogation of lossy mode resonance between absorbing thin film lossy modes and the evanescent wave for measurement of variation in the refractive index of the bulk media. It is shown that a low index dielectric matching layer introduced between the prism and the lossy waveguiding layer can produce an efficient refractive index sensor. The obtained sensitivity (4000–5000 nm/RIU) is comparable to some of the best surface plasmon resonance (SPR) sensors. Unlike the SPR sensor in which surface plasmons can be excited only by p-polarized (TM) light, the proposed sensor can operate at either of these polarizations. Detailed theoretical analysis of the proposed sensor based on Fresnel reflection coefficients and transfer matrix method is presented. Effect of losses (imaginary part of refractive index) on the sensor parameters is also presented in sufficient details. Various parameters such as resonance angle, film thickness and refractive index of various layers are optimized for maximum evanescent field enhancement and increased sensitivity.

1. Introduction

In recent years the transparent conducting oxide films and in particular the indium-tin-oxide (ITO) thin films find their application in liquid crystal displays, flat panel displays, organic LEDs and solar cells. These films are also of importance in adlayer surface chemistry [1,2]. An integrated optic TE/TM pass polarizer with ITO cladding has also been proposed [3]. Since ITO is a transparent conducting oxide and is chemically stable, it offers new technological opportunities in sensing applications. At present, most of the publications on sensors are based on surface plasmon resonance (SPR) phenomenon [3–7]. Surface plasmons are longitudinal charge density waves, which propagate at the interface of two media with real part of their respective dielectric constants having opposite signs [8–12]. These surface plasmon (SP) waves can be excited by only p-polarized incident light under the condition of attenuated total internal reflection using a prism or by using metal clad waveguides. The Kretschmann configuration, composed of a prism coated with a thin metal (generally Ag or Au) film, has commonly been employed for optical sensors using SPR coupling. The excitation of SPs corresponds to attenuation (minimum) of reflected light intensity of SPR curve at a critical angle. Other configurations based on SPR are (i) the long range surface plasmons resonance (LRSPR) in which a dielectric layer is introduced between the prism and metal layer of Kretschmann configuration (ii) the plasmon waveguide resonance (PWR), which has a waveguiding layer between the metal (on prism) and the medium to be sensed and (iii) the waveguiding coupled SPR (WCSPR) which consists of two metal layers and a waveguide layer in between [10–13].

Theoretically the refractive index sensitivity of the conventional Kretschmann SPR sensors is the highest and is best for thin silver (Ag) films. However, Ag films are highly susceptible to oxidation and are not suitable for Kretschmaan configuration. So Ag films need to be coated with either a dielectric layer or a lesser reactive metal like gold (Au). But this leads to reduce refractive index sensitivity. Further, in biosensing applications the sensors should be sensitive for refractive indices around 1.33. The SPR sensors (particularly the integrated optical waveguide coupled SPR sensors) require a high index over layer to shift the operating point towards aqueous environment which again reduces the sensitivity [14]. These limitations can be overcome if we use sensors employing thin conducting oxides such as indium tin oxide (ITO). There are two types of modes supported by ITO thin films. These are the SP modes and the lossy modes. The surface plasmon resonance in ITO films has been studied extensively and their application as chemical sensors has been proposed [1,2]. However, the SPR effect in these films occurs for the wavelength range of 1.8–2.5 μm. Light sources in these wavelength ranges are not easily available. The sensitivity of these sensors is also not high. In the visible and near IR region

* Corresponding author. Tel.: +91 01124116178; fax: +91 01124119832.
E-mail addresses: avinashi_kapoor@yahoo.com, avinashi@south.du.ac.in (A. Kapoor).

http://dx.doi.org/10.1016/j.snb.2014.03.058
0925-4005/

(0.4–1.5 μm) the ITO films have large real part of index and smaller imaginary part. Therefore the ITO films support the lossy modes at these wavelengths [15]. Similar to SPR, these lossy modes can also cause resonance called lossy mode resonance (LMR). In this paper, we will investigate theortically our proposed sensor based on the lossy mode resonance (LMR).

2. Lossy modes supported by ITO films:

All the materials are characterized by their relative permittivity. ITO layers absorb light and are thus characterized by a complex value of relative permittivity. The oscillatory model represents the dielectric constant of ITO films at room temperature and can be expressed [15] as:

$$\varepsilon(\omega) = \varepsilon_\infty - \frac{\omega_p^2}{\omega^2 + i(\omega/\tau)} \tag{1}$$

where ε_∞ is the high frequency dielectric constant = 3.57, τ is the electronic scattering time = 6.34×10^{-15} s/rad and ω_p is the plasma frequency = 1.89×10^{15} rad/s.

When more complex model is used, the better definition of the ITO refractive index is expressed as:

$$\varepsilon(\omega) = \varepsilon_\infty - \frac{\omega_p^2}{\omega^2 + i(\omega/\tau)} + \frac{s_o\omega_o^2}{\omega_o^2 - \omega^2 - i\gamma\omega} \tag{2}$$

s_o is the oscillator strength = 0.49, ω_o is the oscillator resonance frequency = 5.61×10^{15} rad/s and γ is the oscillator damping constant = 9.72×10^{13}.

If the ITO layers are coated on the silica substrate then its real part of refractive index will always be higher than that of the substrate in the wavelength region of our study. Also the index of clad (analyte) above the ITO film is about 1.3, the structure will support guided modes. However these modes will be lossy because of imaginary part of index of ITO films. Thus the dispersion curves for this structure (silica\ITO\dielectric (1.33)) will be similar to the dielectric (lossless) waveguides [3]. The number of modes supported by this waveguide will increase as the ITO thickness increases. However, the mode loss is maximum if the thickness of the ITO layer corresponds to the cut off thickness for that particular mode [16]. In one of the previous studies, it has been shown that if an ITO layer is deposited on the single mode waveguide, then at its particular thickness the mode losses for either TE or TM become maximum [3]. This happen due to the lossy nature of the ITO film and the phase matching between the guided mode supported by lossless dielectric waveguide and the lossy mode supported by the ITO thin film. There is a periodic coupling between the guide waveguide mode and the lossy mode in absorbing film [3]. But if the ITO films are deposited directly on substrate (without guiding film) then the evanescent wave interacts with the lossy mode of the ITO film. The effective index of the evanescent wave can be expressed as $n_{eff} = n_p \sin\theta_i$, where n_p is the index of silica layer and θ_i is the angle of incidence. Effective index can be varied by changing either the angle of incidence or wavelength. For a particular angle or wavelength the effective indices of the evanescent wave and the mode supported by the ITO film may match and the coupling will become maximum. Thus energy is absorbed by the lossy layer and there is a minimum in the reflectivity curve. This phenomenon can be used for designing sensors.

3. Structure and analysis method:

We have studied two structures. First is the conventional Kretschmann configuration. In this configuration (Fig. 1) the lossy ITO film is placed between the dielectric medium (to be sensed) and the prism. This configuration allows the light to exploit

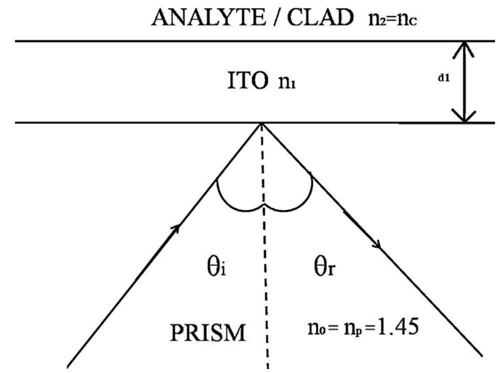

Fig. 1. Kretschmann configuration.

reflecting properties of a prism based on the concept of attenuated total reflection. The reflectivity from the ITO layer can be close to zero at optimum structure parameters. Second is our proposed structure which includes a low index dielectric layer between the prism and the ITO layer.

We calculated the reflectance for both the structures using Fresnel reflection coefficients (Appendix A). Reflectivity analysis is done for both angular and spectral interrogation of all the considered optimized structures. The results are verified by waveguide mode theory. The complex propagation constant of the multilayer structure is obtained by solving the complex eigenvalue equation which is derived using the transfer matrix method (TMM) (Appendix B). TMM can be extended to any number of layers and is easy to formulate. The complex eigenvalue equation describing the structure is exactly solved numerically by Muller Method [17]. Field profiles for various structures are generated. The relevant field enhancement factors are also calculated.

4. Results and discussions:

4.1. Spectral analysis:

4.1.1. Kretschmann configuration:

Let us first consider the Kretschmann configuration (Fig. 1). A thin ITO film is placed on silica substrate. The ITO film thickness is optimized for a minimum in the reflectivity curve. For an optimized angle of incidence (which must be chosen carefully to give minimum reflectivity), the reflectivity becomes minimum at a particular wavelength. This is done for any one of the refractive indices (here 1.33) of our interest. So the ITO film thickness, the angle of incidence and the wavelength at which the reflectivity minima occur are all optimized. If we change the refractive index of the dielectric medium (to be sensed) without changing the angle of incidence, the resonance dip (reflectivity minimum) will be shifted to some other wavelength. The wavelength shifts to higher value if dielectric medium index is higher than the index at which it was actually optimized. The shift will be toward shorter wavelength if the dielectric medium index is smaller. The wavelength dependent reflectivity curves are shown in Fig. 2. Reflectivity is minimum because of the resonant coupling of the evanescent wave and the lossy mode supported by the ITO film at cut off supported by the ITO film. As the index of the dielectric clad is increased, the mode cut off takes place at higher wavelength and at lower wavelength when index of the dielectric is decreased. Since this sensor does not involve SPR, it can be operated at both TE and TM polarization. However the optimum ITO thickness differs. The reflectivity versus wavelength plots as shown in Fig. 2(a) and (b). The sensitivity with TE polarization is 969 nm/RIU and 1170 nm/RIU for TM