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Comparing optical sensing using slab waveguides and total internal reflection ellipsometry

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Abstract

The sensitivity of the effective refractive index of slab waveguide sensors to variations in the refractive index of the cladding is compared to that of the ellipsometric parameters. The changes of the effective refractive index of a waveguide and the ellipsometric parameter Δ, due to the index change of the cladding, were derived and plotted as a function of the guiding layer thickness and with the index of the cladding. It is found that these changes almost have the same overall feature but the ellipsometric parameters showed considerable higher sensitivity than the effective index of the conventional waveguide optical sensors.

Key Words: Optical sensors, slab waveguides, sensitivity, ellipsometry

1. Introduction

Both slab waveguides [1–3] and ellipsometers [4–6] can be used for biosensing. In slab waveguides, fundamental modes TE_0 and TM_0 are used for optical sensing. The essential part of a slab waveguide sensor consists of a high refractive index guiding layer embedded between a substrate and the sample medium to be analyzed, which is called the cover or cladding. In the conventional slab waveguide sensor structure, the substrate is a solid material, which has a refractive index larger than that of the cladding. When a light beam is coupled into a planar waveguide, the light is guided through the guiding layer by a series of total internal reflections at the core-cladding and the core-substrate interfaces. An evanescent wave is formed at each point of total internal reflection along the propagation direction. The evanescent wave distributes a small part of the wave into the cladding and the substrate media to a distance comparable with the wavelength of the guided light. This evanescent wave is responsible for the sensing operation. When an analyte is placed in the evanescent field, a change is observed in the intensity or the phase of the light propagating in the waveguide, giving an indication of the concentration or refractive index of the analyte. One of the most important parameters in optical waveguide sensing is the effective refractive index N of the guided mode. A change is induced in the effective refractive index for any evanescent wave-analyte interaction. This is the basic integrated optical waveguide sensor effect. Optical waveguide sensing is currently of high interest in pharmaceutical applications such as immunoassays, detection of harmful gases (methane, CO_2, SO_2), monitoring pollutants in water, and detecting the concentrations of certain chemicals in blood.

Another technique that can provide information regarding the sensing processes as well as the properties of multilayer structures is ellipsometry. Ellipsometry is an optical technique that measures changes in the reflectance and phase difference between the parallel and perpendicular components of a polarized light beam upon reflection from a surface. Aside from providing a simple, sensitive, and nondestructive way to analyze thin films, ellipsometry allows dynamic studies of film growth (thickness and optical constants) with a time resolution that is relevant to biomedical research.

The thin film sensitivity and the possibility to make in situ measurements at solid/liquid interfaces make ellipsometry an attractive tool for applications in the life science area. A large number and variety of applications of ellipsometry are found in physics, metrology, biology, biochemistry, and chemistry.

The method of total internal reflection ellipsometry and surface plasmon resonance showed great potential for bio-sensing as very sensitive optical analytical techniques. Total internal reflection ellipsometry is employed to investigate the interaction of molecules with surfaces, an area that is of fundamental importance to a wide spectrum of disciplines in cell and molecular biology. Examples are binding and triggering of cells by hormones, neurotransmitters, and antigens; cell adhesion to surfaces; electron transport in the mitochondrial membrane; cytoskeletal and membrane dynamics; cellular secretion events; polymer translation near an interface; single molecule interactions; and surface effects on reaction rates.

The purpose of this article is to compare between the sensitivity of optical planar waveguide sensors and that of total internal reflection ellipsometry.

2. Theory

2.1. Theory of waveguides

Figure 1 shows a thin dielectric guiding layer of thickness h and refractive index n_f embedded between a cladding and a substrate of refractive indices n_c and n_s, respectively. The z-direction is taken to be the longitudinal axis and the angle of incidence is θ_i.

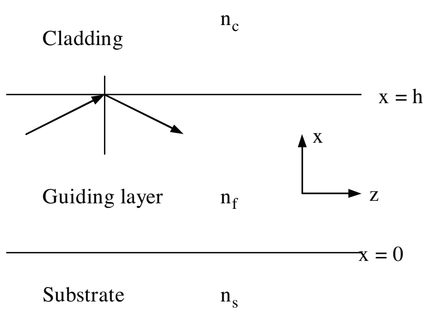

Figure 1. Three-layer planar waveguide system comprising substrate, guiding film, and a cover medium, with refractive indices n_s, n_f, and n_c, respectively.

It is straightforward to show that the mode equation of such a system is given by [7]

$$2k_0h\sqrt{n_f^2 - N^2} + \varphi_c + \varphi_s = 2m\pi, \tag{1}$$

where k_0 is the free space wave number, m is the mode order, and φ_c and φ_s are the phase shifts that the wave undergoes upon totally reflected at the core-cladding and the core-substrate interfaces, respectively. The phase shifts φ_c and φ_s are given by [7]

$$\varphi_c = -2\arctan\left[\left(\frac{n_f}{n_c}\right)^{2\rho}\sqrt{\frac{N^2-n_c^2}{n_f^2-N^2}}\right], \tag{2}$$

$$\varphi_s = -2\arctan\left[\left(\frac{n_f}{n_s}\right)^{2\rho}\sqrt{\frac{N^2-n_s^2}{n_f^2-N^2}}\right], \tag{3}$$

where $\rho = 1$ for TM_m and $\rho = 0$ for TE_m modes.

The sensitivity of the optical waveguide sensor to cover refractive index variations can be obtained by differentiating equation (1) with respect to N [7, 8], we get

$$\frac{\partial N}{\partial n_c} = \left(\frac{n_c}{N}\right)\left(\frac{n_f^2-N^2}{n_f^2-n_c^2}\right)\left(\frac{\Delta x_c}{h+\Delta x_c+\Delta x_s}\right)\left[2\left(\frac{N}{n_c}\right)^2-1\right]^{\rho}, \tag{4}$$

where Δx_c and Δx_s are the penetration depths of the evanescent wave into the cover and the substrate, respectively. The penetration of the guided wave from the guiding layer into the surrounding media is given by [9]

$$\Delta x_{c,s} = \frac{1}{2k_0N}\frac{\partial\varphi_{c,s}}{\partial\theta_i}, \tag{5}$$

where the phase shifts φ_c and φ_s are related to the incidence angle θ_i through the propagation constant in z-direction β given by

$$\beta = k_0 n_f \sin\theta_i = k_0 N. \tag{6}$$

2.2. Theory of ellipsometers

First we briefly introduce the analysis of the phase of the reflected light using ellipsometry [10, 11]. In ellipsometry, two parameters, ψ and Δ, are measured by applying a probe beam with a known polarization state into a sample and then investigating the polarization state of the reflected beam. In reflection mode, the parameters ψ and Δ are given as

$$\tan\psi = \frac{|r_p|}{|r_s|}, \tag{7}$$

and

$$\Delta = \delta_p - \delta_s, \tag{8}$$

where $r_p = |r_p|\exp(i\delta_p)$ and $r_s = |r_s|\exp(i\delta_s)$ are the complex Fresnel reflection coefficients for p- and s-polarized light, respectively.

At total internal reflection, at the clad-film interface, δ_s and δ_p can be written as [12]

$$\delta_s = 2\ \arctan\left[\frac{-u}{\cos\theta_i}\right], \tag{9}$$

$$\delta_p = 2\ \arctan\left[\frac{-u\ n_f^2}{n_c^2\cos\theta_i}\right], \tag{10}$$

where $u = \sqrt{\sin^2\theta_i - \left(\frac{n_c}{n_f}\right)^2}$.

In a similar manner to equation (4), we differentiate equations (9) and (10) with respect to n_c to derive the sensitivity of the ellipsometer as an optical sensor to cover refractive index changes; we obtain

$$\frac{\partial\delta_s}{\partial n_c} = \frac{2}{u\cos\theta_i}\frac{n_c}{n_f^2\left[1+\frac{u^2}{\cos^2\theta_i}\right]}, \tag{11}$$

and

$$\frac{\partial\delta_p}{\partial n_c} = \frac{-2\left[\frac{-1}{n_c u\cos\theta_i} - \frac{2n_f^2 u}{n_c^3\cos\theta_i}\right]}{1+\left(\frac{n_f}{n_c}\right)^4\frac{u^2}{\cos^2\theta_i}}. \tag{12}$$

3. Results and discussion

In the calculations below we consider $m = 0$ corresponding to the fundamental mode. We also consider the clad to be air, the guiding layer to be crystalline silicon (c-Si), and the substrate to be SiO_2. The mode equation given by equation (1) has been solved numerically for the effective index N, we then calculate $\partial N/\partial n_c$ using equation (4) for TE_0 and TM_0 modes. The incidence angles corresponding to these modes are calculated using equation (6). These angles are substituted into equations (11) and (12) to find $\partial\delta_s/\partial n_c$ and $\partial\delta_p/\partial n_c$ which, in turn, are used to calculate $\partial\Delta/\partial n_c$ using equation (8). Variations of $\partial N/\partial n_c$ for TE_0 mode and $\partial\delta_s/\partial n_c$ with the guiding layer thickness are shown in Figure 2, whereas the variations of $\partial N/\partial n_c$ for TM_0 mode and $\partial\delta_p/\partial n_c$ with the guiding layer thickness are shown in Figure 3. The behavior of $\partial N/\partial n_c$ with the guiding layer thickness for both TE_0 and TM_0 modes can be explained as follows. At small values of h, near the cut-off thickness of each mode, $\partial N/\partial n_c$ approaches zero. In this limit, all the mode power propagates in the substrate due to the infinite penetration depth in the substrate [8, 13]. Consequently, the sensor probes the substrate side only and the cover index changes have no influence on the effective refractive index. In the other limit, far beyond the cut-off thickness, $\partial N/\partial n_c$ approaches zero again, which means that all the power propagates in the guiding layer due to the high confinement of the wave. Between these two limits, there is a maximum in the curves, just above the cut-off thickness, representing an optimum value where a relatively large part of the total mode power propagates in the cover medium. As can be seen from the two figures $\partial N/\partial n_c$ for both TE_0 and TM_0 modes, $\partial\delta_s/\partial n_c$ and $\partial\delta_p/\partial n_c$ almost have the same behavior with the guiding layer thickness with the observation that $\partial\delta_s/\partial n_c$ and $\partial\delta_p/\partial n_c$ have much higher values than $\partial N/\partial n_c$ for both modes.

In ellipsometry, the phase change is usually expressed in terms of Δ rather than in terms of δ_s and δ_p, so it is worth studying the sensitivity of Δ to change in cover index. Figure 4 shows the variations of $\partial N/\partial n_c$ for TE_0 and TM_0 modes and $\partial\Delta/\partial n_c$ as a function of guiding layer thickness. The figure reveals that Δ is much more sensitive to cover index changes than the effective index of a waveguide in the whole span of thicknesses. It also reveals that the high sensitivity of Δ is reached at a thickness between the optimal thicknesses of TE_0 and TM_0 modes. In Figures 2–4 we assume the cover to be air with refractive index of unity. For homogeneous sensing the cover may be a gaseous or a liquid so it is important to study the variations of the sensitivity of waveguide sensors and ellipsometers with the cover index n_c. The variations of $\partial N/\partial n_c$ for TE_0 and TM_0

modes and $\partial N/\partial n_c$ with n_c are illustrated in Figure 5. All of the sensitivities increase with increasing n_c since the evanescent field in the cover is enhanced with increasing n_c/n_f at constant n_s/n_f. Again, $\partial\Delta/\partial n_c$ exhibits considerably higher values than $\partial N/\partial n_c$, emphasizing that ellipsometry is more sensitive to cover index changes than slab waveguides in optical sensing.

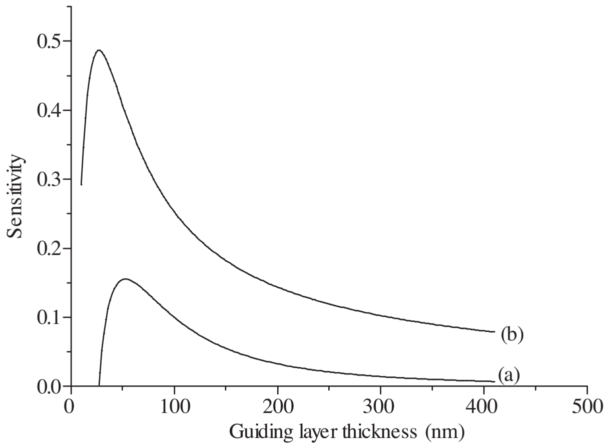

Figure 2. Variations of (a) $\partial N/\partial n_c$ for TE_0 mode and (b) $\partial\delta_s/\partial n_c$ as functions of guiding layer thickness. Parameters for calculation: $n_c = 1$, $n_f = 3.481$, $n_s = 1.528$, and $\lambda = 1.5$ μm.

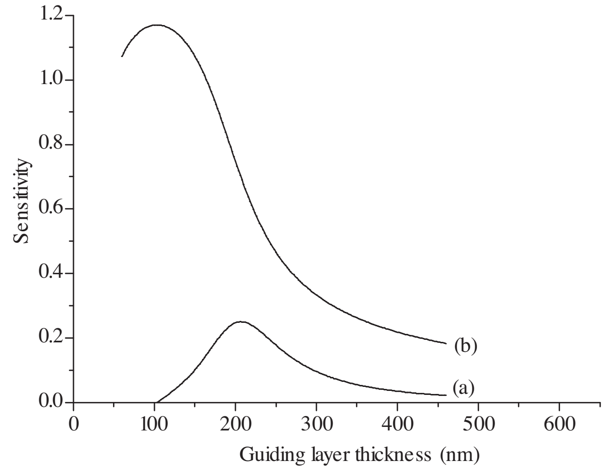

Figure 3. Variations of (a) $\partial N/\partial n_c$ for TM_0 mode and (b) $\partial\delta_p/\partial n_c$ as functions of guiding layer thickness. The same parameters were used in the calculations as in Figure 2.

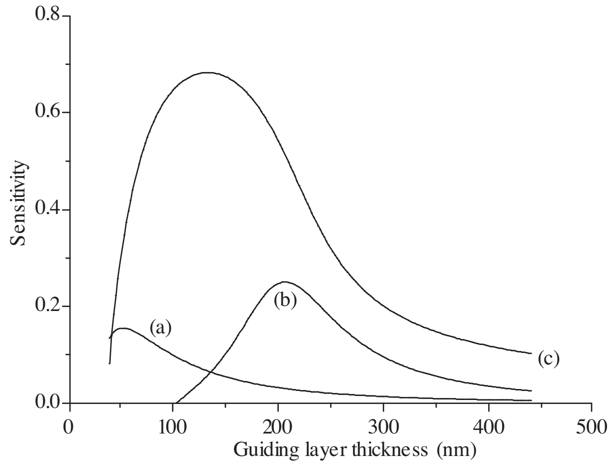

Figure 4. Variations of (a) $\partial N/\partial n_c$ for TE_0 mode, (b) $\partial\Delta/\partial n_c$ for TM_0 mode, and (c) $\partial\Delta/\partial n_c$ as a function of guiding layer thickness. The same parameters were used in the calculations as in Figure 2 and Figure 3.

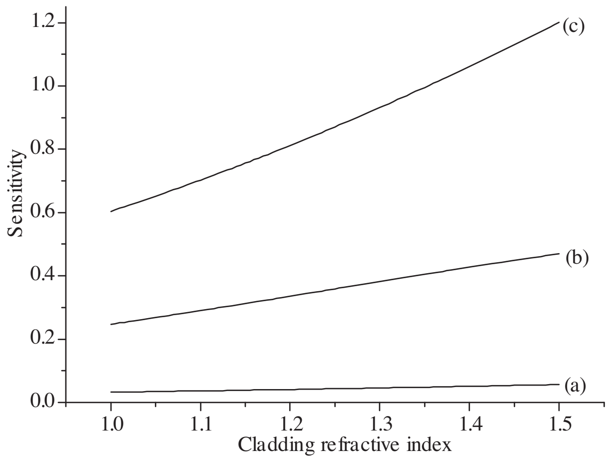

Figure 5. Variations of (a) $\partial N/\partial n_c$ for TE_0 mode, $\partial N/\partial n_c$ TM_0 mode, and (c) $\partial\Delta/\partial n_c$ as a function of cladding refractive index n_c. Parameters for calculation: $n_f = 3.481$, $n_s = 1.528$, $h = 200$ nm and $\lambda = 1.5$ μm.

4. Conclusion

In this work we have compared two optical sensors, a slab waveguide sensor and an ellipsometer at total internal reflection configuration. A brief theory of both is presented with a special focus on their sensitivities. The comparison between the two optical sensors shows that the ellipsometric parameters are much more sensitive to the cover index changes than the effective index of the slab waveguides.

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