Sensors and Actuators B 216 (2015) 247–254

Contents lists available at ScienceDirect

Sensors and Actuators B: Chemical

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

Surface plasmon resonance prism coupler for gas sensing based on Stokes polarimetry

Quoc-Hung Phan[a], Pei-Ming Yang[a], Yu-Lung Lo[a,b,*]

[a] Mechanical Engineering Department, National Cheng Kung University, Tainan 701, Taiwan
[b] Advanced Optoelectronic Technology Center, National Cheng Kung University, Tainan 701, Taiwan

ARTICLE INFO

Article history:
Received 8 December 2014
Received in revised form 8 April 2015
Accepted 9 April 2015
Available online 22 April 2015

Keywords:
Surface plasmon resonance
Stokes polarimetry
Effective ellipsometric parameters
Gas sensing

ABSTRACT

A surface plasmon resonance prism coupler comprising a half-ball lens, an isotropic Cr–Au layer and a Ta_2O_5 anisotropic layer is proposed for gas sensing applications. In the proposed approach, the coupler is illuminated with polarized light and a Stokes polarimetry approach is used to measure the change in six effective ellipsometric parameters as the coupler is exposed to gas samples with different refractive indices. The theoretical analysis is performed to investigate the sensitivity of the effective ellipsometric parameters to the refractive index of the detected gases. The validity of the proposed method is confirmed by comparing the experimental results for the sensitivity of the effective ellipsometric parameters with the analytical results. The results show that the coupler has a sensitivity of 7.5×10^4 deg/RIU (refractive index units) and a sensing resolution of 2×10^{-7} RIU in the indices dynamic range of 1.0–1.001. In general, the results presented in this study confirm that the proposed surface plasmon resonance coupler provides a simple and reliable solution for gas sensing using a Stokes polarimetry approach.

1. Introduction

Surface plasmon resonance (SPR) is a charge density oscillation at the interface of two media with dielectric constants of opposite signs and has significant potential for sensing applications. Liedberd et al. [1,2] were among the first researchers to demonstrate the potential of SPR-based prism couplers for gas sensing. Since then, many SPR-based methods have been proposed for bio/chemical sensing [3–5] and gas sensing [6–8]. Generally speaking, existing SPR sensors are based on either prism couplers or diffraction gratings. However, Homola et al. [9] showed that SPR sensors using prism couplers have a better sensitivity and resolution than those based on gratings in most cases. In 2004, Arwin et al. [10] proposed a prism coupler-based SPR sensor called spectroscopic total internal reflection ellipsometry (TIRE) by combining spectroscopic ellipsometry and SPR. Nabok et al. [11] has proved that TIRE has a better sensitivity as compared to the conventional ellipsometry or SPR method. In recent years, TIRE was employed for biological sensing applications. Le et al. [12] used TIRE to detect successfully microRNAs on the UV/O_3 treated PMMA films. Marin et al. [13] proposed a glutathione (GSH) immunosensing based on TIRE detection that can be enhanced by using gold nano particles modified with GSH. Also, Balevicius et al. [14,15] utilized TIRE to study the optical anisotropy of biorecognition molecule layer and the interaction of biomolecule layers. However, the spectroscopic design in TIRE is complex. Furthermore, the mechanism of TIRE system on these studies only based on the sensitivity of two ellipsometric parameters Ψ and Δ. Consequently, the accuracy and range of its potential applications are both rather limited if only two ellipsometric parameters are considered.

The present study proposes a prism coupler-based SPR sensor for gas detection purposes based on a Stokes polarimetry approach. Notably, in contrast to the method proposed in [10–15], the measurement process is based on six effective ellipsometric parameters, where these parameters are defined in previous studies by the present group [16,17]. The validity of the proposed approach is confirmed by comparing the experimental results for the sensitivity of the ellipsometric parameters to changes in the refractive index of the sensed media with the simulation results for four different gases, namely CO_2, NH_3, N_2 and air. To the best of the authors' knowledge, this study represents the first reported attempt in the literature to perform SPR prism coupler-based gas sensing based on effective ellipsometric parameters and a Stokes polarimetry approach.

* Corresponding author at: Mechanical Engineering Department, National Cheng Kung University, Tainan 701, Taiwan. Tel.: +886 62757575.
E-mail address: loyl@mail.ncku.edu.tw (Y.-L. Lo).

http://dx.doi.org/10.1016/j.snb.2015.04.050
0925-4005/© 2015 Elsevier B.V. All rights reserved.

2. Stokes polarimetry method for extracting effective ellipsometric parameters

Any optical system can be described as $S = [M]_{\text{sample}} S'$, where S is the Stokes vector of the output light yielded by the 4×4 Mueller matrix $[M]_{\text{sample}}$ and S' is the Stokes vector of the input light. The general form of this relation is given as

$$\begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \end{bmatrix} = \begin{bmatrix} m_{11} & m_{12} & m_{13} & m_{14} \\ m_{21} & m_{22} & m_{23} & m_{24} \\ m_{31} & m_{32} & m_{33} & m_{34} \\ m_{41} & m_{42} & m_{43} & m_{44} \end{bmatrix} \begin{bmatrix} S'_0 \\ S'_1 \\ S'_2 \\ S'_3 \end{bmatrix} \tag{1}$$

Given the use of five different input lights, namely four linear polarization lights (0°, 45°, 90° and 135°) and one right-hand circular polarization light, proving the sufficient equations to determine the complete Muller matrix $[M]$ in Eq. (1). The corresponding input Stokes vectors are as follows: $S'_{0^\circ} = [1, 1, 0, 0]^T$, $S'_{45^\circ} = [1, 0, 1, 0]^T$, $S'_{90^\circ} = [1, -1, 0, 0]^T$, $S'_{135^\circ} = [1, 0, -1, 0]^T$, and $S'_R = [1, 0, 0, 1]^T$, the output Stokes vectors are then obtained as

$$S_{0^\circ} = [m_{11} + m_{12}, m_{21} + m_{22}, m_{31} + m_{32}, m_{41} + m_{42}]^T \tag{2}$$

$$S_{45^\circ} = [m_{11} + m_{13}, m_{21} + m_{23}, m_{31} + m_{33}, m_{41} + m_{43}]^T \tag{3}$$

$$S_{90^\circ} = [m_{11} - m_{12}, m_{21} - m_{22}, m_{31} - m_{32}, m_{41} - m_{42}]^T \tag{4}$$

$$S_{135^\circ} = [m_{11} - m_{13}, m_{21} - m_{23}, m_{31} - m_{33}, m_{41} - m_{43}]^T \tag{5}$$

$$S_R = [m_{11} + m_{14}, m_{21} + m_{24}, m_{31} + m_{34}, m_{41} + m_{44}]^T \tag{6}$$

For an anisotropic sample, the ellipsometric parameters include the amplitude ratio Ψ and phase difference Δ of the p- and s-waves of the polarized light as they pass through the sample. In general, the normalized Jones matrix of an optical sample is given as

$$U_i = \begin{pmatrix} u_{11} & u_{12} \\ u_{21} & u_{22} \end{pmatrix} = \begin{pmatrix} r_{\text{pp}} & r_{\text{ps}} \\ r_{\text{sp}} & r_{\text{ss}} \end{pmatrix} = r_{ss} \begin{pmatrix} \frac{r_{\text{pp}}}{r_{\text{ss}}} & \frac{r_{\text{ps}}}{r_{\text{ss}}} \\ \frac{r_{\text{sp}}}{r_{\text{ss}}} & 1 \end{pmatrix}$$

$$= r_{\text{ss}} \begin{pmatrix} \rho_{\text{pp}} & \rho_{\text{ps}} \\ \rho_{\text{sp}} & 1 \end{pmatrix} \tag{7}$$

where

$$\rho_{\text{pp}} = \frac{r_{\text{pp}}}{r_{\text{ss}}} = \tan(\Psi_{\text{pp}}) \exp(j\Delta_{\text{pp}})$$

$$\rho_{\text{ps}} = \frac{r_{\text{ps}}}{r_{\text{ss}}} = \tan(\Psi_{\text{ps}}) \exp(j\Delta_{\text{ps}})$$

$$\rho_{\text{pp}} = \frac{r_{\text{sp}}}{r_{\text{ss}}} = \tan(\Psi_{\text{sp}}) \exp(j\Delta_{\text{sp}})$$

The 16 elements of the Mueller matrix are obtained by transforming its Jones matrix as [16]. It is noted that each element m_{ij} is expressed as function of Ψ_{pp}, Ψ_{ps}, Ψ_{sp}, Δ_{pp}, Δ_{ps}, and Δ_{sp}.

In the previous study by the present group [17], the concept of "effective ellipsometric parameters" was introduced, in which the p- and s-waves considered in traditional ellipsometry techniques were redefined as p′- and s′-waves with a P′–S′ coordinate system, and were orientated at an arbitrary angle of θ relative to the original X–Y coordinate system. Furthermore, the two traditional ellipsometric parameters, Ψ and Δ, were redefined as six effective ellipsometric parameters, i.e., Ψ'_{pp}, Ψ'_{ps}, Ψ'_{sp} and Δ'_{pp}, Δ'_{ps}, Δ'_{sp}, where these parameters describe the amplitude ratio and phase difference, respectively, between the p′- and s′-waves. For an anisotropic material, the effective ellipsometric parameters fall within the ranges of $0^\circ \le \Psi'_{\text{pp}} \le 90^\circ, 0^\circ \le \Psi'_{\text{ps}} \le 90^\circ, 0^\circ \le \Psi'_{\text{sp}} \le 90^\circ, 0^\circ \le \Delta'_{\text{pp}} \le 360^\circ, 0^\circ \le \Delta'_{\text{ps}} \le 360^\circ, 0^\circ \le \Delta'_{\text{sp}} \le 360^\circ$, and can be expressed in terms of the measured Stokes parameters as

$$\Psi'_{\text{pp}} = \tan^{-1}\left(\frac{S_{0^\circ}(0) + S_{0^\circ}(1)}{S_{90^\circ}(0) + S_{90^\circ}(1)}\right)^{1/2} \tag{8}$$

$$\Psi'_{\text{ps}} = \tan^{-1}\left(\frac{S_{90^\circ}(0) + S_{90^\circ}(1)}{S_{90^\circ}(0) - S_{90^\circ}(1)}\right)^{1/2} \tag{9}$$

$$\Psi'_{\text{sp}} = \tan^{-1}\left(\frac{S_{0^\circ}(0) - S_{0^\circ}(1)}{S_{90^\circ}(0) - S_{90^\circ}(1)}\right)^{1/2} \tag{10}$$

$$\Delta'_{\text{ps}} = \tan^{-1}\left(\frac{-S_{90^\circ}(3)}{S_{90^\circ}(2)}\right) \tag{11}$$

$$\Delta'_{\text{sp}} = \tan^{-1}\left(\frac{2(S_R(0) - S_R(1)) - (S_{90^\circ}(0) - S_{90^\circ}(1))(\tan^2(\Psi_{sp}) + 1)}{2(S_{45^\circ}(0) - S_{45^\circ}(1)) - (S_{90^\circ}(0) - S_{90^\circ}(1))(\tan^2(\Psi_{sp}) + 1)}\right) \tag{12}$$

$$\Delta'_{\text{pp}} = \tan^{-1}\left(\frac{(S_{135^\circ}(3) - S_{45^\circ}(3)) - (S_{90^\circ}(0) - S_{90^\circ}(1))(\tan(\Psi_{\text{sp}})\tan(\Psi_{\text{ps}})\sin(\Delta'_{\text{ps}} - \Delta'_{\text{sp}}))}{(S_{45^\circ}(2) - S_{135^\circ}(2)) - (S_{90^\circ}(0) - S_{90^\circ}(1))(\tan(\Psi_{\text{sp}})\tan(\Psi_{\text{ps}})\cos(\Delta'_{\text{ps}} - \Delta'_{\text{sp}}))}\right) \tag{13}$$

To investigate the effects of experimental errors in the measured output Stokes vectors on the accuracy of the extracted effective ellipsometric parameters, the values of Ψ'_{pp}, Ψ'_{ps}, Ψ'_{sp}, Δ'_{pp}, Δ'_{ps}, Δ'_{sp} were calculated theoretically using Eqs. (8)–(13) for an anisotropic film sample with assumed parameters of $\Psi'_{\text{pp}} = 50^\circ$, $\Psi'_{\text{ps}} = 20^\circ$, $\Psi'_{\text{sp}} = 20^\circ$, $\Delta'_{\text{pp}} = 70^\circ$, $\Delta'_{\text{ps}} = 80^\circ$ and $\Delta'_{\text{sp}} = 80^\circ$ and were compared with the input values. (Note that the assumed parameters are based on the simulation results obtained in the following section for the case where the sensitivity of the effective ellipsometric parameters to the refractive index of the sensed gas is the highest.) The corresponding results are presented in Fig. 1(a)–(c) for output Stokes vectors with assumed accuracies of ±0.5%, ±0.05% and ±0.005%, respectively. In Fig. 1(a), the extracted values of Ψ'_{pp}, Ψ'_{ps}, Ψ'_{sp}, Δ'_{pp}, Δ'_{ps} and Δ'_{sp} are found to deviate from the input values by ±0.0015°, ±0.006°, ±0.006°, ±0.014°, ±0.01°, and ±0.03°, respectively. An inspection of Fig. 1(b) shows that the errors in the extracted values of the effective ellipsometric parameters decrease by one order as the accuracy of the Stokes vectors increases from ±0.5% to ±0.05%. A similar result occurs when the accuracy of the Stokes vectors is increased by a further order from ±0.05% to ±0.005% (see Fig. 1(c)), the error between the extract and input values are one order smaller.

3. Sensitivity of effective ellipsometric parameters to changes in refractive index of sensed medium

Fig. 2 presents a schematic illustration of the SPR optical sensing system proposed in this study. As shown, the system comprises a half-ball lens, an isotropic thin film layer, an anisotropic layer, and the sensed gas. The half-ball lens serves to couple the incident polarized light into the isotropic film and provides total internal reflection. Meanwhile, the isotropic/anisotropic layers enhance the sensing performance by manipulating the incident polarized light and provides SPR conditions. The sensitivity of the effective ellipsometric parameters to changes in the refractive index of the sensed gas was examined by means of numerical simulations.

In conducting the simulations, the half ball lens was assumed to be made of BK7 glass with a refractive index of $n_0 = 1.517$ while the isotropic layer was assumed to be fabricated of Cr–Au with a