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Sensitivity of surface plasmon resonance sensors based on metallic columnar thin films in the spectral and angular interrogations

Atef Shalabney[a,*], C. Khare[b], B. Rauschenbach[b,c], I. Abdulhalim[a]

[a] Department of Electro Optic Engineering and The Ilse Katz Institute for Nanoscale Sciences and Technology, Ben Gurion University of The Negev, Bear Sheva 84105, Israel
[b] Leibniz Institute of Surface Modification, Permoserstrasse 15, 04318 Leipzig, Germany
[c] University Leipzig, Institute for Experimental Physics II, Linnéstr. 5, 04307 Leipzig, Germany

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ABSTRACT

Surface Plasmon Resonance (SPR) from metallic Columnar Thin Films (CTFs) of porosity as high as 0.5 was experimentally and theoretically investigated. The CTF layers were prepared by the Glancing Angle Deposition (GLAD) method. The SPR features were investigated in both the angular and the spectral modes. In the angular interrogation, increasing the porosity causes broadening to the dip width, shift to larger resonance angles, and increase of the sensitivity to analyte refractive index (RI) changes by about threefold compared with closed metal films. In the spectral interrogation, on the other hand, the resonance wavelengths are red-shifted for porous films; hence their spectral sensitivities are higher than those of closed films under the same experimental conditions. Nevertheless, the sensitivity behavior versus the resonance wavelength is similar to that of SPR sensors based on dense film layers. The shapes of the nanostructures constituting the CTF are described as ellipsoidal inclusions in which the effective permittivity dyadic of the composite material is calculated using the Bruggeman formalism with exact depolarization dyadics. The correlation between the sensitivity enhancement and the electromagnetic field intensity at the interface between the metallic film and the analyte was examined. Electromagnetic fields analyses were performed using the general 4×4 propagation matrices of general homogenous biaxial layers.

1. Introduction

Optical resonant phenomena are used for sensing, particularly when associated with surface evanescent waves since they are usually associated with a narrow peak or dip in the reflection/transmission/absorption or scattering spectra. Confined to the metal\dielectric interface, surface plasmon (SP) waves are recognized to be extremely sensitive to changes in the dielectric region within the penetration depth of the evanescent field [1]. This remarkable property has been used for the development of label-free plasmonic biosensors, which recently emerged as a promising modern technology for detection and studies of biochemical events on metal surfaces [2]. Exciting an SP wave can be achieved by a p-polarized incident light when its wave vector tangential component matches the SP wave vector. This momentum matching condition yields surface plasmon resonance (SPR) which is accompanied with enhanced electromagnetic fields at the metal\dielectric interface [3]. Since the wave vector of the incident light in air is smaller than the wave vector of the SP, SPR can be achieved by either a high refractive index (RI) prism at incidence angles larger than the critical angle of total internal reflection (TIR) or by a one-dimensional grating. Most of the SPR biosensors commercially available at present use the TIR geometry in what is known as Kretschmann configuration. In this configuration, one side of the prism is coated with a thin continuous metal film (usually Ag or Au) and contacts the target dielectric analyte sample to be sensed [4].

Owing to the SPR condition, an enhanced field is generated at the metal\analyte interface which evanescently extinguishes into the analyte region [5]. This evanescent field functions as a measuring probe to the changes in the analyte introduced by variations in the medium RI. An extremely small detection limit exceeding 10^{-7} refractive index unit (RIU) is achievable, and can be further improved using phase-sensitive SPR schemes [6,7]. When the SPR condition is met, namely the specific combination of the wave vector and wavelength of the incident light, the reflectance of the p-polarized incident light strongly decreases and a narrow dip in the reflectance profile is obtained. Tracing the dip location versus changes in the analyte RI imposes the sensing mechanism of SPR

* Corresponding author. Tel.: +972 08 6428597; fax: +972 08 6479494.
E-mail address: shalaban@bgu.ac.il (A. Shalabney).

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sensors, either by measuring the reflectance as a function of the incidence angle when the wavelength is fixed or by measuring the reflectance spectrum for a fixed incidence angle. Another mode of SPR sensing is based on the phase retardation between the reflected and incident light versus RI variations, which is known as phase-sensitive SPR sensing [7].

Sensitivity is a hallmark feature in SPR sensors and has different definitions whether the angular interrogation mode is considered or the spectral interrogation mode is considered [8]. In the angular interrogation, namely the wavelength is fixed; the sensitivity of the sensor is defined as the ratio between the change in the resonance angle and the analyte RI variation. While in the case of spectral interrogation where the incidence angle is fixed; the sensitivity is the ratio between the resonance wavelength change and the corresponding analyte RI variation [9].

Tremendous effort has been dedicated in the last decade to improve the SPR sensors sensitivity. In this aspect, many works were done on optimizing the SPR sensor characteristics such as modifying the prism refractive index [10,11], optimizing the metallic layer [12], and using bi-metallic layer [13]. Additional techniques were introduced by phase-sensitive SPR sensors [14] and fiber-optics based configurations [15]. Furthermore, the use of long range SPR (LRSPR) was proposed to enhance sensitivity, improving the figure of merit (FOM) of the sensor, and increasing the propagation length of the SP waves [16,17]. Adding a thin dielectric layer on the top of the metal layer in the Kretschmann configuration was presented by Lahav et al. which improved the sensitivity by more than twofold [18,19]. The electric field intensity enhancement at the metal\dielectric interface is considered as a key rule in enhancing the sensitivity of SPR sensors. The correlation between the sensitivity enhancement and the EM field intensity was recently examined and confirmed by Shalabney and Abdulhalim for some of the above methods [20]. Recently, a comprehensive review to the SPR sensitivity enhancement methods was presented by Shalabney and Abdulahalim [21].

Surface plasmons can be localized on metallic nanoparticles and nanoshells [22,23]. Localized SPR (LSPR) can also arise at some locations either in or on certain porous or highly disordered materials [24]. The associated absorption resonances often show up in the optical spectra as narrowband features. Spatial non-homogeneities can also lead to average over many different localized resonances, the overall resonance get broadened thereby. Investigating the SPR phenomenon from nano-engineered columnar thin films (CTFs) recently received great interest. Sufficiently thick CTFs are assemblies of upright, parallel columns generally grown by physical vapor deposition (PVD) techniques. Yang et al. [25] deduced the anisotropic optical properties of obliquely evaporated nickel films by SPR measurements in the Otto configuration. In recent works, SPR from thin metallic layer covered with periodic structures of different shapes like nanowires [26,27], nanorods [28], T-shape [29], and periodic nanoslits in metal thin films were also investigated [30,31].

In this paper we investigate both theoretically and experimentally the sensitivity of SPR sensors based on metallic CTFs with various porosity. In a previous work we showed that SPR exists on the surface of porous metallic CTFs and presented theoretically the relationship between the porosity of the CTF and the angular sensitivity of SPR sensor [32]. In the present work we examined the

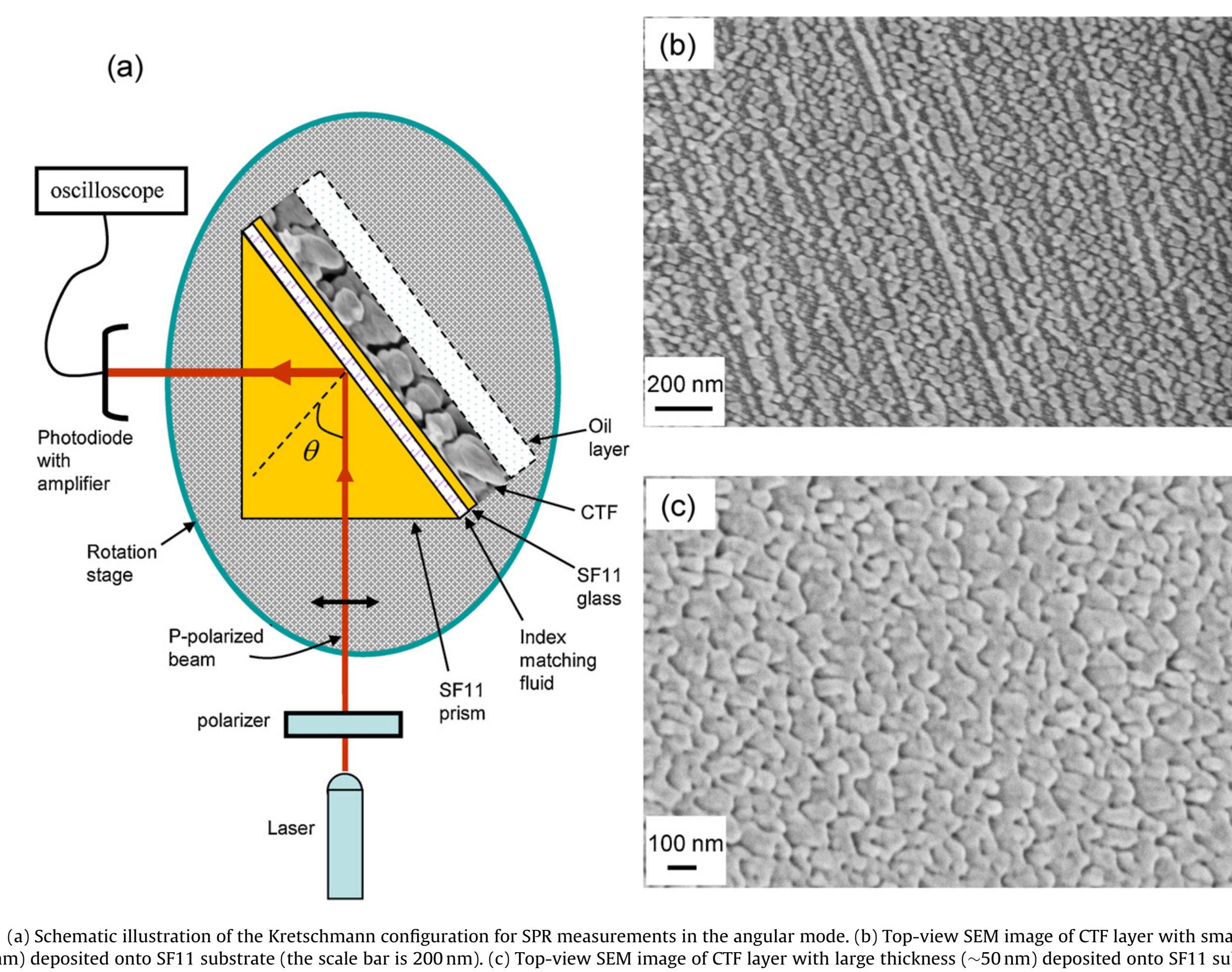

Fig. 1. (a) Schematic illustration of the Kretschmann configuration for SPR measurements in the angular mode. (b) Top-view SEM image of CTF layer with small thickness (~30 nm) deposited onto SF11 substrate (the scale bar is 200 nm). (c) Top-view SEM image of CTF layer with large thickness (~50 nm) deposited onto SF11 substrate (the scale bar is 100 nm).