Sensitivity enhancement of surface plasmon resonance sensors through planar metallic film closely coupled to nanogratings

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We investigate the sensitivity enhancement of surface plasmon resonance (SPR) sensors through planar metallic film closely coupled to nanogratings. The effects of the thickness of metallic film and grating period on the refractive index sensitivity of the device are analyzed in detail. The refractive index sensitivity of nanograting-based SPR sensors is predicted to be about 540 nm per refractive index unit (RIU) using optimized structural parameters. Furthermore, the grating period can be used as a parameter to adjust the wavelength of resonance reflection. Our study on SPR sensors through planar metallic film closely coupled to nanogratings demonstrates the potential for significant improvement in refractive index sensitivity, since it shows much greater flexibility in terms of tuning the optical parameters of the device.

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Optical sensors based on the surface plasmon resonance (SPR) have received significant attention in past few years[1]. In conventional SPR sensors, the performance of the sensors is determined by the surface plasmon polaritons (SPPs) excited on the thin film in the attenuation total internal reflection (ATIR) scheme. However, the development of large scale biosensor arrays composed of highly miniaturized signal transducer elements enables the real-time, parallel monitoring of multiple species to be an important driving force in biosensor research[2]. It is well known that noble metallic nanostructures allow strong optical coupling of incident light to resonance, the so-called localized surface plasmon resonances (LSPRs), which are collective electron oscillations localized in metallic nanostructures. It has been reported that the strong interaction between SPPs and LSPRs and between LSPRs in the present nanostructures can lead to different resonance properties, such as an additional shift of resonance angle or wavelength, changes in the reflectance amplitude and resonance width, resulting in sensitivity enhancement of a SPR sensor[3,4].

In this paper, we investigate the sensitivity enhancement of nanograting-based SPR sensors using rigorous coupled wave analysis (RCWA)[5]. A schematic of the structure used in this study is illustrated in Fig. 1. It consists of a metallic film with thickness d_1 on glass substrate, a separation layer with thickness d_2, and a rectangular metallic grating with height of d_3, a period of Λ, on top of the separation layer. The separation layer and substrate are assumed to be SiO_2 ($n = 1.45$) and BK7 glass ($n = 1.52$). The metallic film and gratings are made of silver with complex refractive index. Optical properties of silver at the incident wavelength are from Ref. [6]. A transverse magnetic (TM) polarized light, the electric field of which oscillates in parallel to the nanograting vector, is incident on the glass substrate at normal incidence. The range of wavelengths in the simulation is from 500 to 850 nm. The parameters fixed in simulations below include SiO_2 layer thickness of 150 nm, Ag grating height of 40 nm, and grating duty cycle of 0.8.

To obtain the reflection spectra from the substrate side, the RCWA is applied to analyze the multilayer film grating structure. The RCWA is based on the resolution of Maxwell equations under the appropriate boundary conditions and involves sophisticated computer calculations. Convergence in RCWA can be achieved by including a sufficient number of space harmonics for the calculation of metallic surface periodic structures. The classical approach has been successfully applied for numerical calculation to explain the experimental results of nanostructures[7,8], offering an effective scheme to analyze optical properties of the metallic and dielectric nanostructures.

Figure 2 shows the effects of different thicknesses of silver film on the reflection spectra of the configuration with grating period $\Lambda = 500$ nm, where the thicknesses of silver film d_1 are varied from 0 to 60 nm. We observe a strong dependence of the reflection resonance peaks on d_1. In the case of $d_1 = 0$ nm, the reflection spectrum shows two peaks at the wavelengths of 500 and 750 nm, which can be identified as the air-side peak and SiO_2 dielectric layer-side peak, respectively. When increasing

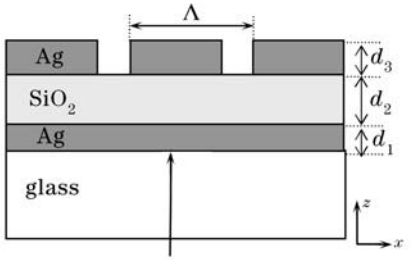

Fig. 1. Schematic diagram of the studied structure formed by a metallic film lying onto a glass substrate, a dielectric layer and a rectangular metallic nanograting on the top. A TM polarized light is incident on the glass substrate at normal incidence. d_1, d_2, and d_3 denote the thickness of Ag film, SiO_2 layer, and Ag nanogratings, respectively.

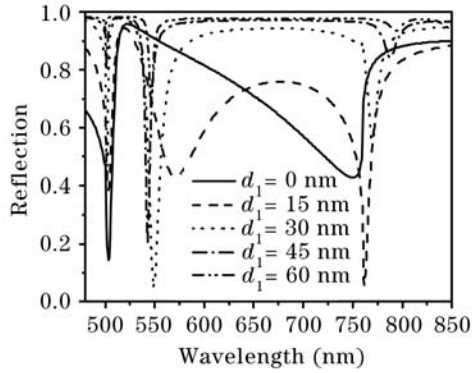

Fig. 2. Reflection spectra with different silver film thicknesses, $\Lambda = 500$ nm.

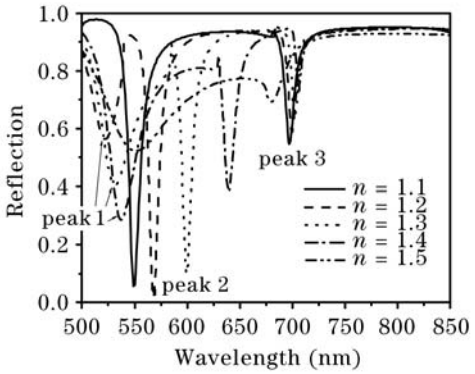

Fig. 3. Evolution of the reflection spectra with the dielectric constant n, $\Lambda = 450$ nm, $d_1 = 30$ nm.

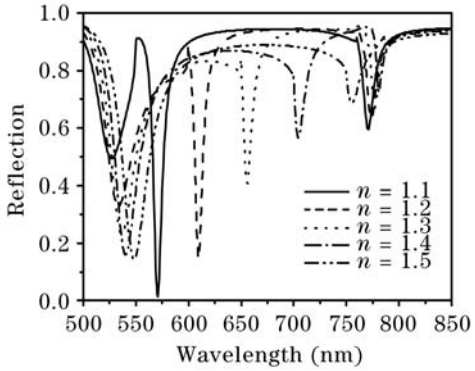

Fig. 4. Evolution of the reflection spectra with the dielectric constant n, $\Lambda = 500$ nm and all other parameters are the same as those in Fig. 3.

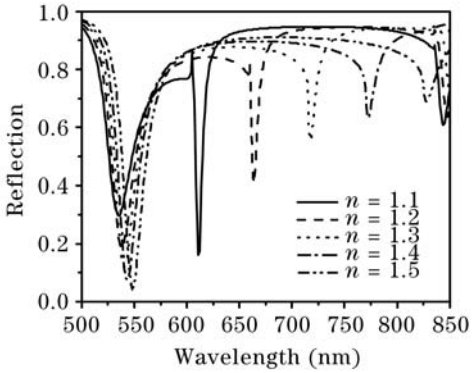

Fig. 5. Evolution of the reflection spectra with the dielectric constant n, $\Lambda = 550$ nm and all other parameters are the same as those in Fig. 3.

the thickness d_1 to 15 nm, the spectrum displays an additional resonance at the wavelength of 570 nm. This can be interpreted in terms of strong interaction between LSPR and SPR modes in the presence of metallic nanogratings and the surface of planar metallic film. Note that the shape of the additional peaks is affected by the thickness of the silver film. For thin silver film, as the thickness d_1 increases, the additional resonance peak shifts towards shorter wavelength, and the resonance bandwidth is narrowed simultaneously. When $d_1 = 30$ nm, the depth of the resonance peak reaches the maximum value. For the film thicker than 30 nm, as the thickness increase, the additional resonance peak diminishes sharply. The simulation results indicate that the existence of planar metallic film results in a sharp resonance reflection peak, and its thickness can be used as a parameter to optimize the depth and full-width at half-maximum (FWHM) of the resonance peak.

In order to evaluate the sensing ability of the system, all surfaces of silver gratings as well as the surface of SiO_2 dielectric layer between gratings are covered by the sample materials. A refractive index ranging from 1.1 to 1.5 is chosen for modeling a sample layer. Biochemical reactions take place in the liquid solutions with typical refractive index values in this range. Most generally, target analytes are injected into the flow channel[9]. Here the refractive index change is induced by binding events of target analytes inside the flow channel and is assumed to represent the concentration change in binding events linearly. Figure 3 shows the evolution of the reflection spectra of the configuration as a function of the dielectric constant n of the sample layer, where grating period is 450 nm, Ag film thickness d_1 is 30 nm. It is clear that three distinct resonance reflectance peaks appear. Peaks 1 and 3 in Fig. 3 are at rough 525 and 700 nm, respectively, which are hardly influenced by the changes of the refractive index. Peak 2 is dependent on the changes of refractive index on top of the silver gratings. As the refractive index n increases from 1.1 to 1.5, peak 2 shifts towards longer wavelength (red shift), and its depth becomes shallow. The resonance shift to an increase of n is completely linear with the sensitivity equal to 328 nm per refractive index unit (RIU).

In Fig. 4, the reflectance spectra of the structure with a grating period of 500 nm are shown. We observe a very strong dependence of the reflection spectra on the grating period. Compared with Fig. 3, it can be found that all reflection peaks shift towards longer wavelength. The refractive index sensitivity is about 460 nm per RIU. The reflectance spectra of the structure with a grating period of 550 nm are shown in Fig. 5. The refractive index sensitivity is more than 540 nm per RIU. Especially, FWHM of the resonance peak at the wavelength of 610 nm is less than 10 nm. Compared with Fig. 4, the resonance dips are shallower.

It can be found from Figs. 3−5, the metallic film closely coupled nanograting structure with a grating period of 550 nm is most sensitive to changes in the refractive index, followed by $\Lambda = 500$ nm and then $\Lambda = 450$ nm. In other words, the refractive index sensitivity is just the

grating period, and larger period will have higher sensitivity. This gain in sensitivity as the grating period increasing is attributed to the strong interactions between LSPRs in the presence of nanogratings. When grating period increases, the resonant LSPR-LSPR coupling strongly affects the sensitivity enhancement. Moreover, it is clearly seen that the resonance peaks shift towards longer wavelength as the grating period increases. Consequently, the grating period can be used as a parameter to adjust the wavelength of the resonance reflection.

In conclusion, we present a highly sensitive nanograting-enhanced SPR sensor. The results show that the reflection properties of the device are strong dependent on the thickness of metallic film. When the thickness of the metallic film is more than 15 nm, the additional resonance peak appears, which is highly sensitive to small variations in the dielectric constants of the sample on top of the metallic nanogratings. We predict that a refractive index sensitivity of more than 540 nm per RIU can be obtained using the optimized structure. The optical configuration of normal incidence and high refractive index sensitivity makes it possible for SPR sensors.

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