A novel biosensor with enhanced sensitivity based on grating coupled double-layered porous silicon waveguide*

LÜ Xiao-yi（吕小毅）[1], **MO Jia-qing**（莫家庆）[2,3], **ZHANG Hong-yan**（张红燕）[4], **ZHONG Fu-ru**（钟福如）[2], and **JIA Zhen-hong**（贾振红）[2]**

1. Postdoctoral Station of Computer Science and Technology, Xinjiang University, Urumqi 830046, China

2. Colleges of Information Science and Engineering, Xinjiang University, Urumqi 830046, China

3. School of Electronic and Information Engineering, Xi'an Jiaotong University, Xi'an 710049, China

4. School of Physics, Xinjiang University, Urumqi 830046, China

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The enhanced sensitivity of a guided mode biosensor is analyzed by employing double-layered porous silicon grating structures. The grating-coupled waveguide structure consists of two porous silicon grating layers with different refractive indices. Simulations are carried out by changing the refractive index, which is due to the binding of biological molecules on the porous silicon pore can increase the refractive index of porous silicon. The numerical results show that this novel guided mode biosensor with a double-layered grating can provide not only a very high sensitivity but also a better reflectivity characteristic.

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Porous silicon (PSi) has attracted a great deal of attention for biochemical sensing applications due to its large surface area and easy preparation[1-5]. In order to enhance the performance of PSi-based biosensors, various novel PSi-based photonic configurations have successfully been employed for the detection of chemical and biological molecules, including grating waveguide, resonant photonic structures, Bragg mirrors, diffraction gratings, and so on[6-11]. Recently, Xing Wei and Sharon M. Weiss[8] reported that using all-PSi singal-layer grating-coupled waveguide biosensors for detecting biomolecules has many advantages, and it was shown to be highly efficient. The research inspires us to design and investigate a novel PSi-based resonant grating waveguide with double-layered grating structure.

In this paper, a PSi-based grating coupled waveguide using double PSi grating layers with different refractive indices for biosensing has been demonstrated. It is noted that the double-layered PSi grating structure has higher sensitivity, nearly two times of that of the all-PSi single-layer grating-coupled waveguide biosensors in Ref.[8]. Moreover, the double-layered PSi grating structure shows a better reflectivity characteristic with a narrower peak and a higher intensity. The novel PSi grating coupled waveguide opens the door for designing all-silicon sensor for sensing various chemical, and biological species, and can also be applied in narrow bandpass filter.

Fig.1 shows a schematic diagram of the proposed PSi-based guided mode biosensor, which is based on Ref.[8], and the difference is that the single layer grating structure is changed into double layers with different refractive indices. According to Ref.[8], the double-layered PSi samples can be prepared from p-silicon with 0.01 Ω•cm by electrochemical etching, the top PSi can be formed approximately at 5 mA/cm^2 for 30 s, and the bottom grating layer is formed at 48 mA/cm^2 for 17 s.

In order to compare the performance between the PSi-based guided mode biosensor with double-layered grating and the all-PSi single-layer grating structure in Ref.[8], the parameters of the proposed structure are employed as Ref. [8]. The height of the top PSi grating with the refractive index of n_{g1}=1.8 is h_{g1}= 70 nm, and the height of the bottom grating layer with the refractive index of n_{g2}= n_s (refractive index of substrate)=1.21 is h_{g2}= 65 nm, so the total thickness of grating is 135 nm. The grating period is Λ=1685 nm, the thickness of

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** E-mail: jzhh@xju.edu.cn

PSi waveguide layer is h_w= 190 nm, the refractive index of waveguide layer is n_w=1.8, the thickness of substrate is h_s=1500 nm, and the air fill factor is 50%. Incident light wavelength is λ=1550 nm (TE), and the spectrum is characterized by a 1550 nm laser due to the low absorption coefficients of PSi in the infrared region .

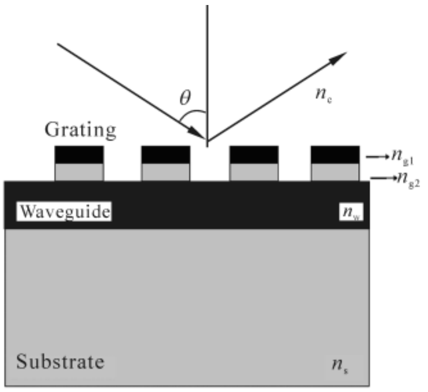

Fig.1 Schematic diagram of the proposed PSi-based guided mode biosensor

According to Ref.[8], the reflectivity of the PSi-based guided mode biosensor is a function of the coupling angle θ, and the angle θ changes with the effective refractive index caused by attaching biomolecules[4], and the well-known fundamental principle of coupling condition is defined as follows[8]:

$$n_c \sin\theta \pm m\frac{\lambda_0}{\Lambda} = n_{\text{eff}} \ , \qquad (1)$$

where n_c is the refractive index of air (cover layer as shown in Fig.1), Λ is the grating period, m is an integer, λ_0 is the incident light wavelength, θ is the coupling angle, and n_{eff} is the effective refractive index of the guide mode.

Using the analytical methods in Refs.[8] and [10], the simulations of reflection spectra of PSi-based resonant grating are carried out by rigorous coupled wave analysis (RCWA), and herein we use the commercial RSoft-DiffractMOD codes.

Fig.2 shows the theoretical reflection spectrum of the single-layer grating structure described in Ref.[8]. We can see that the angular reflection spectrum we calculated is consistent with the result calculated in Ref.[8]. Based on the same calculations, the theoretical reflection spectrum of the proposed PSi biosensor with a double-layered grating is shown in Fig.3. Compared with Fig.2, a sharper peak is exhibited in Fig.3, and it presents a high Q factor ($\lambda/\Delta\lambda$), which means the sensitivity of the sensor is enhanced with higher Q factor[12]. Besides, it also has higher optical reflectivity which can be better used in the actual detections.

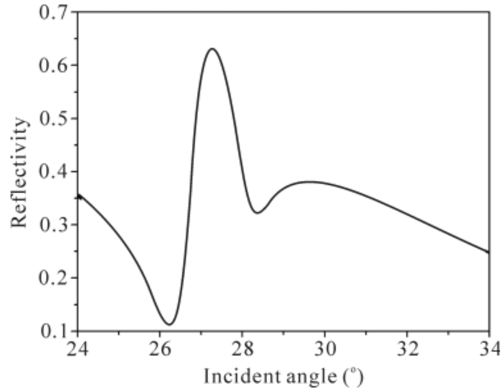

Fig.2 Theoretical reflection spectrum of the single-layer grating structure described in Ref.[8]

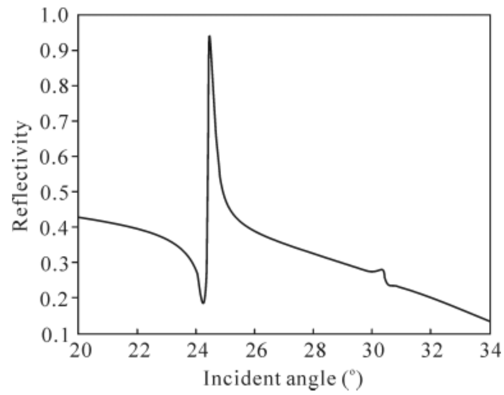

Fig.3 Theoretical reflection spectrum of the proposed PSi biosensor with a double-layered grating

Researchers have found that binding of biological molecules can increase the refractive index of the PSi layers[4], and the refractive index changes approximately from 0.01 to 0.05[10]. The simulated resonance spectra of PSi-based resonant grating before and after attaching biomolecules are shown in Fig.4. The selected increase of the refractive index of all PSi parts is Δn=0.04. Fig.4(a) shows simulated angle-resolved spectra of the single-layer structure described in Ref.[8] before and after attaching biomolecules, which causes a resonance shift of 1.3°. And Fig.4(b) shows simulated angle-resolved spectra of the double-layer structure with a shift of 2.6°, which is just about two times of that of the all-PSi single-layer grating-coupled waveguide biosensors in Ref.[8]. According to Ref.[10], the slope of the simulated data points represents the sensitivity of the biosensor, and the pore index is changed due to the binding of biological molecules. The reflection spectrum is characterized by the same simulations as Ref.[10], and Fig.5 shows the simulated resonance shifts with refractive index changing. In Fig.5, our PSi-based resonant grating shows a higher slope of 68.6, the resolution is 0.001°, and the detection limit is 1.46 × 10^5 RIU, which are all better than the results in Ref.[10]. Simulations show that the double-layer PSi-based resonant grating has higher sensitivity of detection than the reported PSi waveguide biosensor.

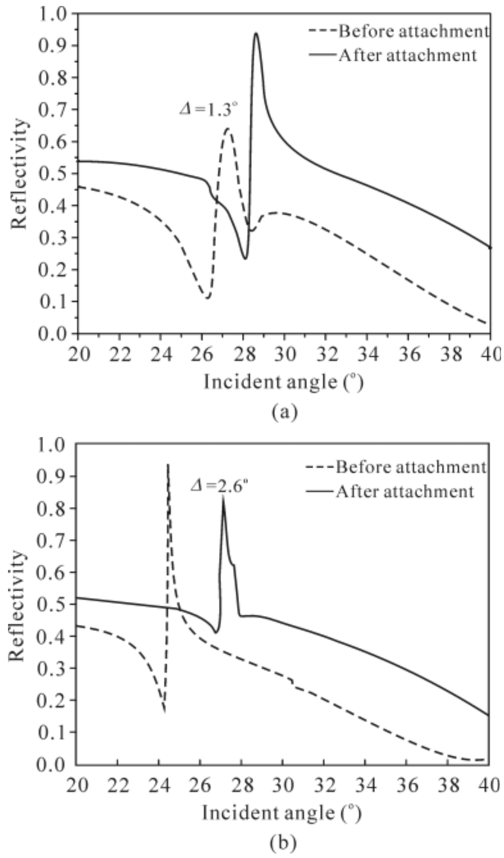

Fig.4 Simulated angle-resolved spectra of (a) single-layer structure and (b) double-layer structure before and after attaching biomolecules with Δ*n*=0.04

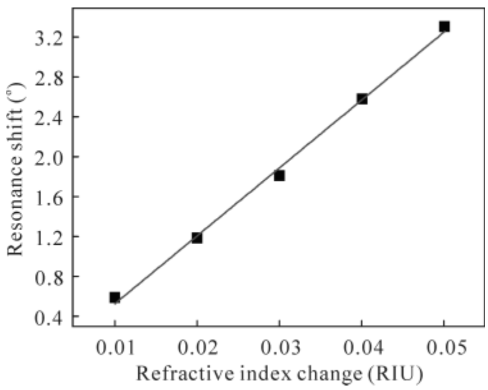

Fig.5 Simulated resonance shift with refractive index changing

In conclusion, a novel PSi biosensor based on double-layer resonant grating with different refractive indices is proposed. It is demonstrated that as an optical sensor platform, PSi based resonant grating with double layers has a higher sensitivity and higher reflectivity for easy detection. Furthermore, it remains the advantages of PSi biosensor, such as large surface area, easy preparation. Thus, this study is expected to play a potential role for the extensive applications in all-silicon biosensor.

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