Compact biosensors based on thin film silicon nitride microring resonators

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Abstract. We presented a silicon microring resonator based on thin film silicon nitride waveguide for biosensor applications. Design and fabrication were conducted. The device was fabricated on a silicon nitride wafer with 250 nm top film on 3 µm buried oxide by using electron-beam lithography and inductively coupled plasma etching. The radius of the microring is as smaller as 50 µm. The quality factor of the resonator is 8610. The spectra and resonance shift for bulk sensing were measured by flowing sodium chloride solutions with different concentrations on the surface of the sensor. The sensitivity and the LOD of the sensor are 384.58 nm/RIU and 4.68×10⁻⁴ RIU, respectively.

1. Introduction

Biosensors and chemical sensors have become active research fields because of the promising applications in enormous fields such as cancer diagnostics, blood testing, environmental monitoring, and safety system. Sensors based on optical waveguide have attracted lots of interests due to the compact size and integration capability. There are many different structures of optical waveguide based sensors including Mach-Zehnder sensors, grating assisted sensors, multi-mode waveguide sensors, plasma waveguide sensors, and microring resonator sensors[1-5]. In order to strengthen the interaction between the optical field and the detecting media, it is better to let the detecting media enter the maximum region of the optical filed as possible. Thin film waveguides satisfy this requirement attributing to the high power density in the claddings which is covered by low index refractive materials such as water, gas and blood[6-8].

In order to obtain a larger interaction between the optical field and the bio-material, a long waveguide such as spiral is required. However, long optical path will increase the transmission loss, which might deteriorate the performance of the sensor. Microring resonator offers another method to enhance the interaction because the light transits in the ring many times. While the index of analyte changes, the resonance wavelength of the microring will shift. It can be tested by measured the optical spectrum or the intensity. Silicon nitride waveguide has a moderately high index contrast, a relatively high Kerr nonlinearity and a negligible two photon absorption around the telecom wavelengths, which makes it a potential candidate for photonic integration platforms[9-11]. Moreover, silicon nitride has a wide transparent window ranging from visible to near infrared wavelengths[12]. In this paper, we proposed a compact integrated waveguide sensor based on thin film silicon nitride microring resonator with a 50 µm radius. The design and fabrication were presented. The spectrum and bulk sensitivity were measured.
2. Design and operation principles
The thin film silicon nitride channel waveguide is fabricated on the silicon substrate with a SiO₂ claddings with a thickness of 3.0 μm. The width and the thickness of the core are 2.0 μm and 250 nm, respectively, which supports single mode transmission well. The silicon nitride microring resonator is schematically shown in figure 1(a). The light couplings are conducted by using waveguide grating couplers which offer excellent design and application flexibilities[11]. Figure 1(b) shows electric field distribution of the optical fundamental TE mode. It can be seen that a significant part of the optical power distributes in the up cladding. The transmission condition will change while a sensing material is added on the waveguide, which results in a resonance shift of the spectrum of the microring resonator.

![Figure 1. (a) The structure illustration, and (b) optical fundamental TE mode of the biosensor.](image)

When the refractive index (RI) of the sensing material changes, the effective refractive index (Neff) of the waveguide will change. In the case of a resonator, the resonance wavelength will shift with the refractive index changing of the sensing material. The sensitivity (S) is measured in the unit of nm/RIU. The detection limit (LOD) is \( \lambda_0/(Q \cdot S) \), where \( \lambda_0 \) is the resonant wavelength, \( Q \) is the quality factor of the resonator[13, 14].

Figure 2 shows the effective refractive index of the silicon nitride waveguide as a function of refractive index of the up cladding. It was calculated by using FDTD (Finite-Difference Time-Domain) method. Here, we used the RI of NaCl solution for calculation. It can be expressed as \( n = 1.3105 + 0.17151 \times C \), where \( C \) is the mass concentration of NaCl in percentage. It can be seen that the effective index increases quite linearly with the material index increasing. The obvious effective index shift ensures excellent index sensing.

![Figure 2. The effective refractive index of the waveguide.](image)

3. Experimental results and discussions
The 250 nm-thick thin silicon nitride film is firstly deposited on the wafer at a temperature of 150 °C by using the liquid source chemical vapour deposition (LSCVD). A 500 nm-thick positive photoresist
ARP6200 is then spin-coated on the wafer at the speed of 1500 rpm. After baking at 150 °C for 1 minute, the waveguide structure is then patterned by electronic beam lithography (EBL) and etched 250 nm onto the silicon nitride layer by ion coupling plasma (ICP) with the gas of CHF3. The gap flow, bias power and ICP power are 6 scem, 50 W and 50 W, respectively. After removing the photoresist, a 2 µm-thick SiO2 layer is then deposited on the sample as a top cladding at 150 °C by using liquid source chemical vapour deposition. Refractive indices of SiO2, SiN and Si are 1.45, 1.80 and 3.45, respectively. The radium of the ring, the waveguide width, the gap between the bus waveguide and the microring are 50 µm, 2.0 µm and 200 nm, respectively. Figure 3 shows the SEM images of the device.

Figure 3. SEM images of the silicon nitride microring resonator. (a) The top view. (b) The zoom-in image in the coupling region. (c) The image of the waveguide grating coupler.

The light from a tuneable laser was pumped into the grating coupler. The wavelength was swept over a range of 100 nm and the spectrum was recorded by an optical power meter with 1 pm wavelength resolution. The measured transmission spectrum is shown in figure 4(a). The insert shows the measurement setup. Figure 4(b) shows one resonance near the wavelength of 1550 nm. It can be seen that the quality factor $Q$ is about 8610.

Figure 4. Optical spectrum of the SiN microring resonator sensor.

In order to measure the bulk sensitivity, deionized water and NaCl solutions with different concentration were flown over the sensor surface. Note that, a testing window is open in the SiO2 up cladding layer on the microring before the measurement. Between two successive measurements, the sample was cleaned. Figure 5 shows the relationship between the resonance wavelength shift and the refractive index of NaCl solutions flown over the surface of the sensor. The straight line is the linear fit of the data. The sensitivity is 384.58 nm/RIU. The limit of detection (LOD) is calculated to be 4.68×10⁻⁴ RIU. The excellent performance is attributed to the thin film structure and high $Q$ factor of the device. Usually, the sensitivity depends on the optical power distributed in the up cladding. Therefore, it can be improved further by decreasing the thickness of silicon nitride film to an ultra-thin level such as 150 nm and 100 nm.
4. Conclusions
We presented a thin film silicon nitride microring resonator for biosensor application. The radius of the microring is 50 μm. After optimizing the design, the sensor was fabricated by using EBL and ICP etching. The spectra for bulk sensing were measured. The sensitivity and the LOD of the sensor are 384.58 nm/RIU and 4.68×10^{-4} RIU, respectively.

References
[1] Chao, C., Guo, L. J. (2006) Design and optimization of microring resonators in biochemical sensing applications. Journal of Lightwave Technology, 24: 1395-1402.
[2] Murib, M. S., Martens, D., Bienstman, P. (2018) Label-free real-time optical monitoring of DNA hybridization using SiN Mach-Zehnder interferometer-based integrated biosensing platform. Journal of Biomedical Optics, 23: 1-7.
[3] Lorrain, N., Pirasteh, P., Girault, P., Azuelos, P., Lemaitre, J., Guendouz, M., Hardy, I., Thual, M., Charrier, J. (2019) Submicron gap reduction of micro-resonator based on porous silica ridge waveguides manufactured by standard photolithographic process. Optical Materials, 88: 210-217.
[4] Xia, F., Hu, H., Zhao, Y. (2019) Highly-sensitive phase-interrogated RI sensor based on twin-core fiber with inherent noise suppression. Optics and Lasers in Engineering, 120: 66-70.
[5] Wang, Y., Li, S., Kiravittaya, S., Wu, X., Wu, K., Li, X., Mei, Y. (2019) Mode-splitting based optofluidic sensing at exceptional points in tubular microcavities. Optics Communications, 446: 128-133.
[6] Dar, T., Homola, J., Rahman, B. M. A., Rajarajan, M. (2012) Label-free slot-waveguide biosensor for the detection of DNA hybridization. Applied Optics, 51: 8195-8202.
[7] Liu, Q., Tu, X., Kim, K. W., Kee, J. S., Shin, Y., Han, K., Yoon, Y., Lo, G., Park, M. K. (2013) Highly sensitive Mach-Zehnder interferometer biosensor based on silicon nitride slot waveguide. Sensors and Actuators B: Chemical, 188: 681-688.
[8] Lu, G.W., Hong, J.X., Qiu, F., Spring, A. M., Kashino, T., Oshima, J., Ozawa, M., Nawata, H., Yokoyama, S. (2020) High-temperature-resistant silicon-polymer hybrid modulator operating at up to 200 Gbit s^{-1} for energy-efficient datacentres and harsh-environment applications. Nature Communications, 11: 4224.
[9] Hong, J.X., Hong, Y.X., Lin, X., Tan, Z.R., Hu, W.D., Ge, H. (2019) Four-wave mixing in integrated photonic waveguides. In: Eleventh International Conference on Information Optics and Photonics. Xi'an, China. pp. 112092N.
[10] Hong, Y.P., Hong, Y.X., Hong, J.X., Lu, G.W. (2021) Dispersion optimization of silicon nitride waveguides for efficient four-wave mixing. Photonics, 8: 161.
[11] Hong, J.X., Spring, A. M., Qiu, F., Yokoyama, S. (2019) A high efficiency silicon nitride waveguide grating coupler with a multilayer bottom reflector. Scientific Reports, 9: 12988.
[12] Feng, J., Akimoto, R. (2014) A Three-Dimensional Silicon Nitride Polarizing Beam Splitter. IEEE Photonics Technology Letters, 26: 706-709.

[13] Liu, Y., Li, Y., Li, M., He, J. (2017) High-sensitivity and wide-range optical sensor based on three cascaded ring resonators. Optics Express, 25: 972-978.

[14] Yan, H., Huang, L., Xu, X., Chakravarty, S., Tang, N., Tian, H., Chen, R. T. (2016) Unique surface sensing property and enhanced sensitivity in microring resonator biosensors based on subwavelength grating waveguides. Optics Express, 24: 29724-29733.