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HIGHLY SENSITIVE AND INTEGRATED VOC SENSOR BASED ON SILICON NANOPHOTONICS

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ABSTRACT

An integrated volatile organic compounds (VOC) sensor based on silicon photonic ring resonator system is presented in this paper. A thin absorption layer is coated on the silicon surface required to selectively trap the target gas and response as refractive index change, acting as the main sensing unit, which subsequently affect the resonance peak position. The relative high sensitivity (1.7 pm/ 1000 ppm for acetone), high stability (<1 pm drift) and fast response time (~20 s) make it a perfect candidate in VOC safety monitoring and warning.

KEYWORDS

Silicon Photonic, Sensor, Ring Resonator, Volatile Organic Compounds

INTRODUCTION

Gas sensor has grab much attention recent years. It detects the presence of gas in an area, which is often a part of safety system. Combustible, flammable, toxic or pollution gases require to be monitored, avoiding the potential hazard to human or properties. Some gas such as breath acetone is an indicator for diabetes control. With the advantages of high sensitivity, fast response time and compact size, gas sensing via optical methods has been widely investigated. Optical gas sensors detect or distinguish target gas based on their optical properties. By the measured properties, optical gas sensing methods can be categorized into absorption [1], emission [2] and refractive index [3]. Refractive index gas sensors measure the refractive index change caused by target gas, which can be further categorized into interferometer [4, 5], fiber [6, 7] and photonic chip based [8-10].

In this paper, refractive index method based on silicon ring resonator is used, which is CMOS compatible and can be easily integrated with other sensors and control elements. An integrated volatile organic compounds sensor is presented. This on-chip photonic gas sensor is based on refractive index change induced by gas absorption on an absorption layer. Current sensor is tested with acetone vapor, and the detection limit reached 800 ppm, which is lower than the human safety level. This makes it suitable for VOC safety monitoring. By making a ring resonator array, the proposed sensor has a potential to detect and distinguish different gas species.

DESIGN AND ANALYSIS

Figure 1(a) shows the silicon ring resonator sensing platform. There are two main systems in the experimental setup, optical system and the fluidic system. The fluidic system is for gas feeding and waste collection. The optical

system is for detecting the ring resonator transmission spectrum. A broadband light is coupled to the silicon ring via a straight waveguide. The cross-section of the waveguide and the ring is 450 nm × 220 nm (width × thickness). The coupling gap between the straight waveguide and the ring is 200 nm. The ring structure is coated by a thin absorption layer and covered in a microfluidic channel, acting as the main sensing unit. The whole device is built by standard CMOS fabrication process. Figure 1(b) shows the SEM image of the fabricated silicon ring resonators. After light passing through the resonator, resonance peaks can be seen on the output spectrum, which is detected by a germanium photodetector. As shown in Figure 2, the downward peak represents the resonant state of ring resonator. The inset image shows an enlarged peak, indicating the linewidth of each resonant peak less than 30pm, which offers a Q-factor of more than 5×10^4 .

Figure 1: (a) Schematic of the ring resonator sensing platform. (b) SEM image of the fabricated sensing platform.

Figure 2: Transmission spectrum of ring resonator. Inset shows the enlarged peak with width of 28 pm.

This resonance peak is very sensitive to the group index of the ring structure. Therefore, the ring structure is exposed to the surrounding environment and covered in a microfluidic channel. To make it a gas sensor, a thin absorption layer is coated on the silicon surface required to selectively trap the target gas and response as refractive index change, acting as the main sensing unit. When gas is absorbed in the absorption layer, the refractive index and thickness of this layer will change, and subsequently affect the group index of the ring and the resonance peak position. Therefore, the thickness of absorption layer needs to be determined by simulation to make sure of both the effect. In other word, both the thickness and the refractive index will take effect on the ring resonant wavelength and then the resonant wavelength of ring resonator will change. As a result, the concentration of target gas can be measured by monitoring the peak shift. The resonant wavelength change $\Delta\lambda$ can be derived as

$$\Delta\lambda = \frac{\partial\lambda}{\partial n_{clad}} \Delta n_{clad} + \frac{\partial\lambda}{\partial l} \Delta l, \quad (1)$$

where l is polymer thickness. The two partial derivatives of λ are related with the waveguide structure and can be calculated via mode profile analysis. Effective refractive index n_{eff} can be obtained from mode analysis. Figure 3 (a) and (b) shows the mode distribution in the waveguide before and after the absorption layer coating, respectively. The strong light field in the absorption layer will make the device more sensitive to the refractive index and thickness change.

Figure 3: Mode distribution of the waveguide (a) without, and (b) with absorption layer, respectively.

Simulation for the effect of thickness and refractive index is performed in order to optimize the polymer thickness. The two partial derivatives of λ are defined as thickness sensitivity and refractive index sensitivity for $\frac{\partial\lambda}{\partial l}$ and $\frac{\partial\lambda}{\partial n_{clad}}$, respectively. In Figure 4, we varied the thickness of the polymer layer in a range from zero up to 180 nm, at which point the field distribution in the absorption layer is still dominantly evanescent. As can be seen from Figure 4, increasing the polymer thickness exponentially reduce the thickness sensitivity. As evident from the different curves in Figure 4, polymer with higher index has a strong effect on driving wavelength shift.

Figure 4: Thickness sensitivity as the function of polymer thickness and polymer refractive index

Figure 5 shows the refractive index sensitivity as a function of polymer thickness and polymer refractive index at rest. From the result, refractive index at rest has no effect on refractive index sensitivity. And thicker the polymer, higher the refractive index sensitivity. Combining two of the result, thickness have counter effect on thickness and refractive index sensitivity and refractive index of polymer at rest should be as high as possible. However, in a practical case, the refractive index of polymer is fixed. In order to get a higher wavelength shift, the only possible variable is the thickness. And one more parameter related with thickness is the response time. When the polymer is thicker, it will need longer time for gas to dissolve in. This result may offer a guidance for thickness optimization work.

Figure 5: Refractive index sensitivity as the function of polymer refractive index and thickness

FABRICATION PROCESS

The silicon photonic structures are fabricated via standard complementary metal-oxide semiconductor (CMOS) process. The process flow is summarized in Figure 4. 8-inch silicon-on-insulator (SOI) wafer is used. Thickness of the silicon structure layer is 220 nm and the buried oxide layer is 2 μm based on a bulk 725- μm thickness silicon substrate. The grating coupler is firstly patterned via 248-nm deep UV lithography. Followed by reactive ion etching (RIE) process on silicon structure layer. After photo resist strip and clean process, the pattern of grating coupler is transferred on the silicon layer. 70-nm of silicon dioxide is deposit on top via low temperature plasma-enhanced chemical vapor deposition (PECVD), which used as hard mask for silicon layer etching. Then silicon waveguide is patterned by lithography. Two step RIE etching transfer the pattern on SiO_2 hard mask first and then onto the silicon layer. Hard mask is used to ensure the accuracy of RIE etching. Rib structure is patterned after waveguide structure, similar to the previous process. After this step, the silicon structure layer is finished. 2- μm thickness silicon dioxide is deposited on top of the structure by high density plasma CVD. A trench at edge of chip is etched and 40-nm thickness of Al_2O_3 is deposited by atomic layer deposition (ALD). This process is to protect edge of chip during dicing process. Then window structure is patterned on Al_2O_3 layer, which is used as hard mask for following vapor HF release process. The last step is to expose the waveguide structure. Vapor HF is used to etch through the silicon dioxide layer.

Figure 4: Silicon chip fabrication process flow

RESULTS AND DISCUSSIONS

To demonstrate this sensing performance, a 20-nm

polydimethylsiloxane is spin coated on top of the exposed silicon ring resonator as the absorption layer for the VOC vapor. Acetone is chosen as the target gas. Acetone vapor is injected onto the chip surface via a microfluidic channel bonded on top. N_2 is also used as blank control. Figure 4(a) shows the measured spectrum with the presence of N_2 gas and acetone vapor, whereby obvious peak shift is seen. Figure 3(b) shows the monitored peak position as a function of time. The periods with white background represents the condition when pure N_2 gas is injected in the channel. On the other hand, the periods with gray background represents the condition when different concentrations of acetone vapor are injected in the channel. Stable performance and fast response is observed. The response time constant is about 20 s.

Figure 4: (a) Transmission spectrum when N_2 and acetone vapor is injected onto chip surface. (b) Monitored peak position as a function of time when different gases are presented on chip surface.

Figure 5(a) indicates a linear relationship between acetone concentration and resonance peak position. Based on the experimental results, the sensitivity is 1.7 pm/1000 ppm and the detection limit is 800 ppm. P-xylene is also tested with the same method. As shown in Figure 5(b), a sensitivity of 6.637 pm/1000 ppm is achieved, which leads to a detection limit of 200 ppm.

Figure 5: (a) Peak shift vs acetone concentration. (b) Peak shift vs P-xylene concentration.

CONCLUSIONS

In conclusion, a silicon photonic ring resonator system as a highly sensitive VOC sensor is presented in this paper. A sensitivity of 1.7 pm/ 1000 ppm for acetone and 6.637 pm/1000 ppm for P-xylene is achieved, together with high stability (<1 pm drift) and fast response time (~20 s), making it a perfect candidate in VOC safety monitoring and warning.

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