MEMS integrated narrow band infrared emitter and detector for infrared gas sensor

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Abstract. With the development of microfabrication technology, compact, lightweight, inexpensive and portable micro-spectrum detection and analyzing products are expected to be extensively applied in the future commercially. From the viewpoint of power consumption and compact volume, integration of various components on one substrate is desirable. In this work, integrated infrared gas sensor with micro infrared emitter and detector elements based on MEMS technology are developed. The integrated suspended infrared emitter and infrared microbolometers are designed and fabricated on a silicon substrate.

Introduction

Numerous techniques for gas concentration measurements have been developed over the years. These include metal-oxide gas sensors, solid electrolyte gas sensors, capacitive gas sensor, gravimetric gas sensor and optical sensors. The first four methods rely on measuring the change of an electrical quantity of the sensor's active material. This change is caused by adsorption or absorption of chemical species at the surface of the active material. These methods have advantages such as easy and cheap fabrication by standard micro-electronic or micro-mechanical processes, tiny size, or high operating temperature. But the major drawback of the above sensor schemes is their lack of broad range selectivity due to a lack of sensitive materials for every gas and/or due to crosstalk. Another drawback of some of these sensors is short-lived due to the contact nature of active materials with specific gas which leads to the degradation of the active materials of the sensors. Infrared optical gas sensors, however, offer a variety of advantages compared to the sensors described above. The IR absorption detection mechanism is not influenced by the species used for detection so IR spectroscopy-based sensors do not rely on catalytic or electrochemical reactions; they are not prone to depletion or contamination of the surface and have a long period of operation life.

As can be seen, infrared absorption measurements have been considered more advanced than other sensors. The problem with optical devices has been their high price because of the needs of various infrared components like infrared source, infrared detector, two or more filters and gas absorption cell which is mostly with multiple optical elements and complex shape. However, as new technologies are developed and instrument volumes grow, these prices can be decreased by integration and miniaturization. MEMS/NEMS is one of these technologies which can promote these actions [1-4].

In this work, integrated chips with micro infrared emitter and detector elements based on MEMS technology are developed. The integrated suspended infrared emitter and infrared microbolometers are

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designed and fabricated on a silicon substrate. In the integrated devices, the infrared emitting elements have good thermal isolation property and can reach 500°C in tens of milliseconds and the microbolometer elements have one layer of infrared sensitive thin film of vanadium dioxide with high TCR and have measured $D^*(500K,1Hz)$ more than $5 \times 10^8 \text{cmHz}^{1/2} \text{W}^{-1}$ at peak detection wavelength.

2. Narrow-band infrared devices

Infrared devices based on MEMS technology can achieve breakthrough in three aspects. First, thin film based structures replace the bulk material promote the ultrathin optical and mechanical structure and more easy for multifunction integration; Second, micro-fabrication of thermal isolation cavity makes the possibility of electrical modulation of infrared emission signal at higher frequency and low power consumption; Third, array devices can be batch fabricated and eventually lead to high product and low price. In fact, there are a mumble of researching institutes and companies have made commercial success in optical MEMS devices like DMD, micro-bolometer, infrared scene projector based on micro-emitter array and micro-spectrometry.

Narrow-band infrared devices, however, following the conventional MEMS technology to realize specific mechanical, electrical and thermal functions, must pay more attention to how to achieve narrowband filtering function. Without using individual optical filter, advanced schemes are proposed to pattern micro/nano structure on the optical surface to accomplish multiple optical functions. Compared to the realization of other structures for the MEMS devices, optical micro/nano structures are more challengeable.

Among various kinds of optical micro/nano structure, photonic crystal is the most popular structure used in spectral control. Photonic crystals of 1D to 3D have been designed for narrow band thermal emitter. 2D photonic crystals with metal layer incorporating SPP effect were designed. The SPP type microstructure is likely more effective due to field enhancement of coupled excitation and can achieve narrower emission or absorption. Coherent infrared emission can be obtained through SiC grating which supports surface phonon polariton, it can also be obtained through W grating supports surface plasmon polariton. However, the infrared spectrum angular emission distribution is like rainbow which means the spectrum is seriously angular dependent. The effect leads to the fact that the emission spectral width is mainly determined by the view of field of the optical system which possibly loss the narrow band advantage. So schemes for narrow band creation over wide angular range were proposed, such as MDM multilayer plate and MDM grating structures, where M represents metal or metallic like materials, D represents dielectric materials. Thus spectral interference of these kinds of devices is greatly reduced.

3. Integrated structure

We propose an idea to construct infrared gas sensor with integrated sensor chip. The optical schematic diagram is shown in figure 1. The integrated sensor chip is composed of three on-chip elements, i.e. one emitter and two detectors. The working principle of this sensor is based on typical two-channel configuration, which means one channel is for measurement and another is for reference. The advantage of this configuration is that the fluctuation of source power and environment temperature can be lessened. The emitter element emits infrared radiation with central wavelength $\lambda_0$ and bandwidth of $\Delta \lambda_0$, and the two detectors receive radiation with central wavelength $\lambda_1$ and $\lambda_2$ respectively, and with bandwidth of $\Delta \lambda_1$ and $\Delta \lambda_2$ respectively. The bandwidth of emitter is narrow but still larger than the sum of band-widths of the two detectors, that is $\Delta \lambda_0 > \Delta \lambda_1 + \Delta \lambda_2$.

The narrowband mechanism of the MDM structure is related to the electromagnetic modes excitation presented in curve as shown in figure 2, which is derived by transfer matrix method. The structure parameter of MDM is chosen as Au200nm/Silicon450nm/Au12nm. As shown in the figure, there are several kinds of narrow band modes excitation in the mid-infrared independent of incident angle of light. Since these modes are above to the light line, they can be directly excited by the radiation coming from the air side. This scheme reduces the processes of period structure fabrication adopted in conventional schemes. Moreover, if the metal layer is substituted by metal-like conducting...
ceramic such as TiN\textsubscript{x}, emission or absorption spectrum width can be tuned by varying the electrical or optical properties of TiN\textsubscript{x}.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{infrared_gas_sensor.png}
\caption{Optical schematic diagram of infrared gas sensor using integrated chip.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{reflectance_spectrum.png}
\caption{Reflectance spectrum of MDM structure.}
\end{figure}

4. FDTD simulation

To investigate the emission characteristics of the MDM structure, we calculate the emission spectrum in an indirect manner. First we use finite difference time domain (FDTD) method to calculate the reflectance of this structure, and then use Kirchhoff’s law to deduce the emission spectrum from the relation: $\varepsilon_{\lambda,\theta} = A_{\lambda,\theta} = 1 - R_{\lambda,\theta} - T_{\lambda,\theta}$. In this specific structure, the transmittance $T_{\lambda,\theta}$ is zero (as the bottom metallic layer is optical thick), so the emittance can be calculated from the reflectance directly: $\varepsilon_{\lambda,\theta} = A_{\lambda,\theta} = 1 - R_{\lambda,\theta}$.

The metallic-like layer of the MDM structure is TiN\textsubscript{x}, which has a resistivity of about 500 $\mu\Omega \cdot$cm, its optical constant is obtained through fit parameters by assuming material model of Drude–Lorentz-oscillator type to match the experimental reflectivity. Dielectric layer is a mixed multilayer of SiO\textsubscript{2}/VO\textsubscript{x}/silicon, which has a total thickness near to 0.52 $\mu$m. The surface metal layer is a gold layer having a thickness of 0.012 $\mu$m. The optical constants of other materials are all determined by proper model parameters fitting experimental reflectivity datum. The thin VO\textsubscript{x} layer is need for infrared detection, but not necessary for emitter application.

The simulated emittance of the MDM at normal direction is shown in figure 3. The central frequencies is at 4.25 $\mu$m and the bandwidth is nearly 1 $\mu$m. Increasing the conductivity of TiN\textsubscript{x} can make the bandwidth narrower. The narrowest bandwidth we can reach is about 0.1 $\mu$m by using high conductive TiN\textsubscript{x} where its resistivity is about 40 $\mu\Omega \cdot$cm very close to metal.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{emittance.png}
\caption{Simulated emittance of MDM at normal direction.}
\end{figure}
5. Prototype of CO₂ gas sensor

Integrated chip composed of one emitter and two detectors are implemented by MEMS technology. Patterns are created by standard photolithography, thin film deposition and lift-off processes. Wet etching technique is used to make the patterned elements suspended on silicon supported by multiple long arms, with hollow cavity underneath of the elements. In the integrated devices, the infrared emitting elements have good thermal isolation property and can reach 500°C in tens of milliseconds and the detection elements have one layer of infrared sensitive thin film of vanadium dioxide with high TCR and have measured D*:500K,1Hz) more than 5×10⁻⁸ cmHz⁻¹/² W⁻¹ at peak detection wavelength. Two detection elements have different response, one has the largest response at CO₂ detection wavelength of 4.25μm, but another has response at the reference wavelength of 4.6μm. The integrated device is sealed in vacuum and packaged with leadless chip carrier (LCC) in the end.

![Figure 4. Prototype of CO₂ gas sensor module.](image)

![Figure 5. CO₂ concentration measurement from 0 ppm to 3000 ppm](image)

Having the integrated chip, CO₂ gas sensor is constructed by adding a gas absorption cell and an infrared reflective mirror as main components. The prototype of this sensor is shown in figure 4. The test was achieved in a vacuum chamber filled with N₂. The amount of N₂ and CO₂ gas flowing can be precisely controlled through two mass flow controllers.

After calibration and proper signal processing the concentration of gas can be obtained. We have measured standard CO₂ gas mixed in N₂ in the range between 0 ppm to 3000 ppm. The measurement results have demonstrated the capability of infrared microsystem in application of gas detection. Further research will extend to various kinds of gas or liquid sensing applications and also to establish advanced micro-spectrum analysis systems.

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