Miniature CO2 Gas Sensor (1 cm^3) using Silicon Microbolometers and Micro Variable Infrared Filter

Naoki Kishi, Hitoshi Hara, and Hideto Iwaoka
Micromachining Laboratory, Yokogawa Electric Corporation
2061 Miyada-mura, Kamiina-gun, Nagano 399-4394, Japan
phone: +81-265-85-5620 fax: +81-265-85-5646, Naoki_Kishi@yokogawa.co.jp

SUMMARY

A miniature CO_2 gas sensor of 1 cm^3 volume has been developed. Its operating principle is based on non-dispersive infrared (NDIR) dual-beam dual-wavelength measurement. This gas sensor consists of a conventional miniature lamp as an infrared source, a gas cell and an infrared detecting module, that is assembled from two single-crystal silicon microbolometers, a wide bandpass filter and a micro variable infrared filter (MVIF) in a TO-5 package. The resolution (σ) of the CO_2 concentration is 20 ppm at 2000 ppm for the time constant and the roll-off rate of the output low-pass filter of 3 sec and 12 dB/octave, respectively.

Keywords: CO_2 gas sensor, microbolometer, micro variable infrared filter

INTRODUCTION

In various industries, infrared gas sensing has become feasible for consumer and commercial applications. For example, the use of CO_2 detection systems for home safety and building ventilation control has been steadily increasing. NDIR systems that consist of at least an infrared source, an optical filter and a detector are particularly useful for CO_2 sensors. CO_2 has infrared-absorption bands at a characteristic wavelength of about 4.25 µm. Absorption increases with concentration according to Lambert-Beer's law and therefore CO_2 concentration can be measured from the reduction of infrared irradiation at this band. However, the instruments required for NDIR systems are expensive and large, and so both the cost and size need to be reduced.

We propose an NDIR system as a CO_2 sensor using two bolometers and an MVIF as shown in Fig. 1. Both components are made from CMOS compatible materials. The reference signal compensates for measurement signal fluctuations caused by degradation and fouling of the light source. The new design allows the system to be made small and at low cost, and hence many applications can utilize the advantages of NDIR gas sensing.

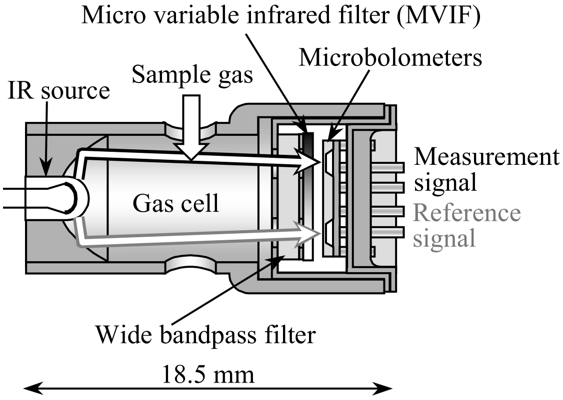

Fig. 1: *Schematic diagram of CO_2 gas sensor.*

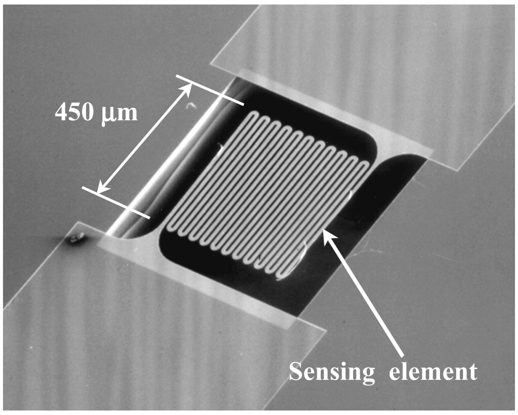

Fig. 2: *Scanning electron microscopy photograph of the sensing element of the silicon microbolometer.*

SILICON MICROBOLOMETER

The two bolometers are made of CMOS compatible materials to meet the demands of reproducibility, uniformity, miniaturization and low cost, and should be a matching pair to improve the performance of the CO_2 gas sensor. We select single-crystal silicon as the material of the bolometer as it can function as both a temperature sensitive resistor and absorber.

The microbolometers are designed to obtain a maximum specific detectivity D^* by using optimization structures and adjusting the concentration of boron in the silicon [1]. Highly doped silicon has low electrical noise and c an absorb infrared rays by free carrier absorption between 3.5 μm and 8.5 μm wavelength. Therefore the boron concentration of $1x10^{20}/cm^3$ is selected. In this case, the value of TCR is 0.2%/K at 300 K. In order to minimize the heat capacitance and the thermal conductance, a thermally isolated structure is formed so that the single-crystal silicon is suspended from the substrate as shown in Fig. 2. This structure is realized using silicon on insulator (SOI) wafers as shown in Fig. 3. The average thermal conductance is measured to be $4x10^{-6}$ W/K in vacuum. The calculated heat capacitance is $3x10^{-7}$ J/K.

This bolometer has a measured D^* (500 K, 10 Hz, 1 Hz) of $1.1x10^8$ $cmHz^{1/2}/W$ in vacuum.

MICRO VARIABLE INFRARED FILTER

The MVIF is a multispectral interference filter on a unique substrate. It has a structure that transforms the center wavelength by changing the thickness of only the spacer layer in the five-layer single halfwave (SHW) type filter [2] as shown in Fig. 4. The substrate of the MVIF is silicon wafer with an antireflection coating of silicon dioxide. The relationship between location and thickness of this layer is controlled using the slit shutter sputtering system. The CO_2 gas sensor uses two wavelengths: The first wavelength is 4.25 μm for measurement, which is absorbed by CO_2. The second wavelength is 4.05 μm for reference, which is not absorbed by CO_2.

Figure 5 shows the spectrum transmission of the MVIF for a CO_2 gas sensor and a wide bandpass filter measured by a spectrometer, together with the absorption bands of CO_2 gas.

NDIR SYSTEM

Infrared detecting module

The infrared detecting module is assembled from the two microbolometers, the wide bandpass filter and the MVIF in a TO-5 package. The wide bandpass filter and the MVIF are mounted in the can with two apertures. The two microbolometers are mounted and wire-bonded in the base as shown in Fig. 6, then the seal

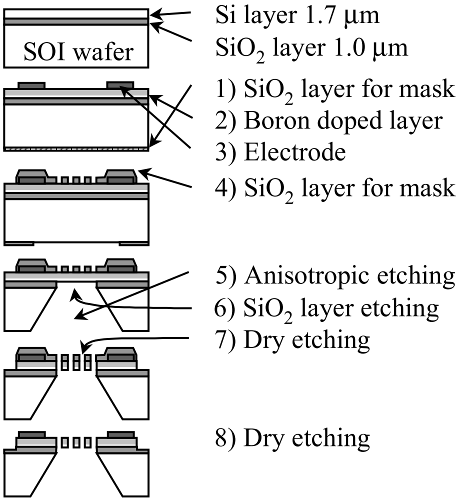

Fig. 3: *Process of fabricating the microbolometer*

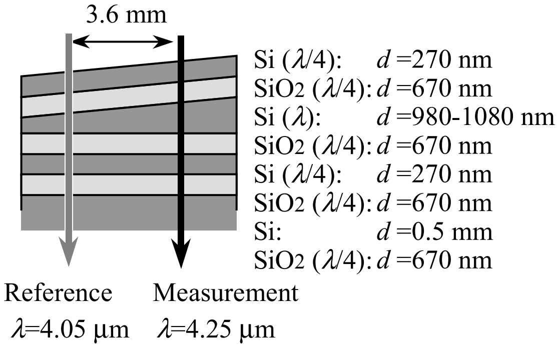

Fig. 4: *Schematic diagram of the MVIF.*

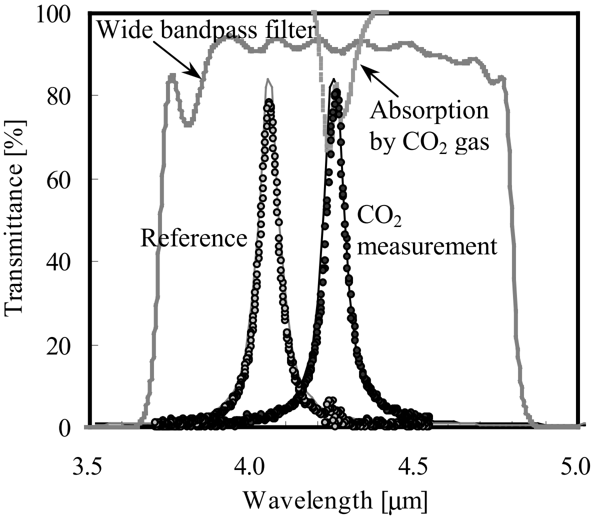

Fig. 5: *Spectral transmission of the MVIF. The solid lines show the calculated results.*

formed between the can and base is made by cold welding in vacuum.

Infrared source and optical system

A conventional tungsten filament lamp of 2.3 mm diameter is selected as the infrared source. Electrical modulation rate of 5 Hz is expected. The maximum temperature of the filament reaches 2000 K at the design current of 115 mA. The glass of the bulb partially absorbs the infrared rays. However, it is possible to obtain sufficient radiant power by the concave mirror as shown in Fig. 1.

The calculated radiant power in one bolometer through the filters is 130 nWrms at the CO_2 concentration of 0 ppm. The NDIR system assembled as a CO_2 gas sensor is shown in Fig. 7.

CO_2 MEASUREMENT

The optical path of the gas cell is 11 mm. In the cell CO_2 gas absorbs infrared radiation at certain wavelengths according to Lambert-Beer's law. Two microbolometers receive the infrared radiation that the filters select for measurement and reference, respectively. The difference between the change in electrical resistance of each bolometer is measured using the bridge circuit as shown in Fig. 8. The assembly of the CO_2 sensor is adjusted precisely so that the rms signal voltage becomes 0 V at the CO_2 concentration of 0 ppm. The two microbolometers with equal performance cancel out extraneous noise and fluctuation caused by the infrared source.

The capability of the CO_2 gas sensor is measured at five points of standard CO_2 gas concentration in the range between 0 ppm to 5000 ppm. The relationship between the concentration of CO_2 and the signal voltage is shown

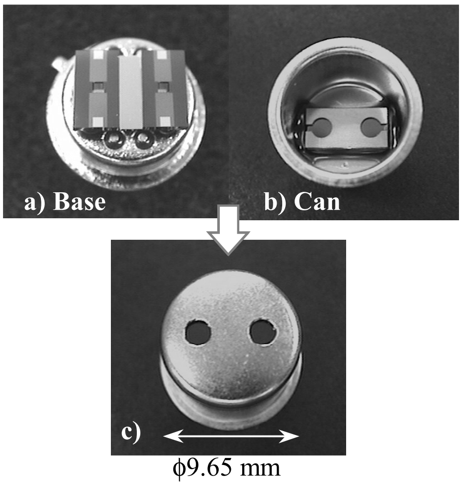

Fig. 6: *Photograph of the infrared detecting module, a) base, b) can and c) top view of the TO-5 package after cold welding.*

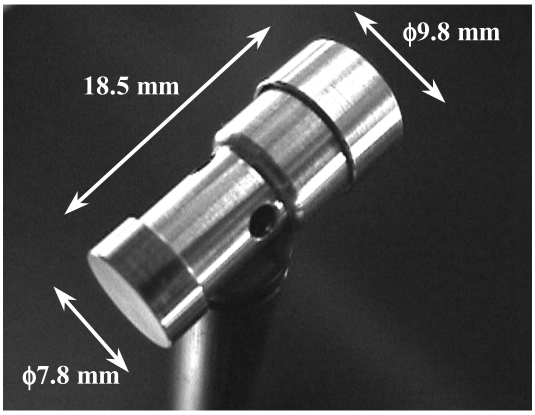

Fig. 7: *Photograph of the CO_2 gas sensor.*

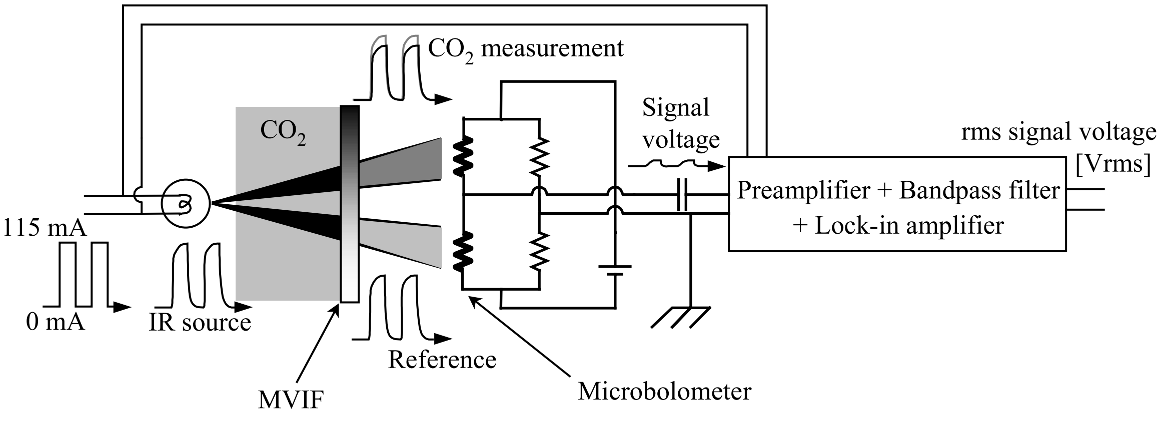

Fig. 8: *The bridge circuit for CO_2 measurement.*

in Fig. 9. The time constant and the roll-off rate of the output low-pass filter of the lock-in amplifier are 3 sec and 12 dB/octave, respectively. The standard deviation σ of rms signal voltage is calculated from 60 samples for 10 minutes at each concentration and σ equivalent resolutions are derived as shown in Table 1. These results demonstrate the possibility using the miniature CO_2 sensors for consumer and commercial installations.

CONCLUSION

A miniature CO_2 gas sensor of comparable size to the chemical-type sensor has been developed. Its σ equivalent resolution of the CO_2 concentration is 20 ppm at 2000 ppm. This CO_2 gas sensor has potential applications in industry, medicine and environmental monitoring.

ACKNOWLEDGMENTS

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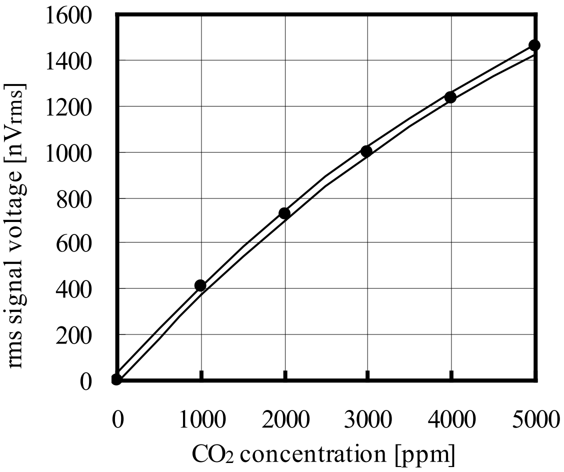

Fig. 9: *CO_2 detection capability, the solid lines show $+3\sigma$ and -3σ of the rms signal voltage.*

Table 1: *CO_2 detection capability and σ equivalent resolution.*

CO_2 concentration	rms signal voltage	Standard deviation of V	σ equivalent resolution
C [ppm]	V [nVrms]	σ [nVrms]	Δ [ppm]
0	1	7.1	17
1000	411	7.4	21
2000	723	6.1	20
3000	993	7.4	28
4000	1230	6.8	30
5000	1458	6.4	34