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Electrothermal Driving Microcantilever Resonator as a Platform for Chemical Gas Sensing*

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Abstract: In the current research, the use of a micromachined cantilever resonator as a platform for chemical gas sensing was examined. The microcantilever resonator integrates an electrothermal driving unit and a piezoresistive detecting unit, and it is fabricated by direct bonding a silicon-on-insulator (SOI) wafer. With a particular polymer layer coated on the surface of the microcantilever, a gas sensor for volatile organic components (VOCs) detection can be realized. The operation mechanism provides the microcantilever resonator with integrated circuit (IC) compatibility in terms of both the fabrication process and operating voltage. The configuration of the microcantilever resonator can optimize the performance of the gas sensor. The SOI wafer provides a solution for the integrated fabrication of the microstructure, transducers, electronics, and the precise control of the resonator parameters. In this paper, the principles, design, analysis, process, and demonstration of the gas sensor based on the microcantilever resonator are presented. The experimental results provide confirmation that the polymer-coated microcantilever resonator has excellent performance with regard to VOC detection.

Key words: microcantilever; resonator; gas sensor; electrothermal driving; volatile organic component

Introduction

Commercially available gas sensors include metal oxide sensors (MOS), conductive polymer (CP) resistors, quartz crystal microbalance (QCM), surface acoustic wave (SAW) sensors, field effect transistors (FET), thermopiles (TMP), and conductive oligomers (CO)[1-4]. In recent years, there has been an increasing interest in the MEMS gas sensor based on the micromachined cantilever because the small size and integrated circuit (IC) compatibility of the microcantilever promise to make it a portable device with high sensitivity and the possibility of large scale array construction. For the gas sensing application, the microcantilever must be functionalized by chemically sensitive material. Polymers have been employed primarily as sensitive materials for the detection of volatile organic compounds (VOCs)[5-8] because the absorption and desorption of the VOCs in the polymers are reversible.

From previous research concerning microcantilever sensors[9-12], two types can be distinguished: the static type and the resonant type. In the static type, the surface stress or bending deflection of the microcantilever is measured; in the resonant type, the resonant frequency of the vibrating microcantilever is detected. It is well known that the frequency measurement is more reliable than the deflection measurement for quantitative analysis because the frequency output is already digitally expressed and can therefore be transmitted more safely from the mechanical domain to the

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electric domain. In addition, silicon micromachining technologies can produce extremely small microcantilevers with high quality and high resonance frequencies for excellent sensor performance, including high sensitivity, faster response, and insensitivity to external disturbances. Therefore, microcantilever resonant sensors have inherently high sensitivity and accuracy, as well as a powerful anti-disturbing capability.

In the current study, a microcantilever resonator was developed for a gas sensing application. In this paper, the principles, design, analysis, process, and demonstration of the gas sensor based on the microcantilever resonator are presented.

1 Principles

1.1 The measurement model

When the gas molecules react with the sensitive layer on the surface of the microcantilever and cause mass loading, the resonant frequency of the microcantilever will change accordingly. The frequency shift $\Delta\omega$ due to mass loading Δm can be expressed by[13]

$$\Delta\omega \approx -\frac{1}{2}\frac{\omega_0}{m}\Delta m \tag{1}$$

where m is the mass of the microcantilever and ω_0 is the fundamental resonant frequency of the microcantilever. Given the volume of the polymer layer on the microcantilever V_{poly}, the mass loading due to polymer-analyte interaction will be

$$\Delta m = c_{\text{poly}} V_{\text{poly}} \tag{2}$$

where c_{poly} is the concentration of the analyte in the polymer phase. The ratio between the equilibrium concentrations of the analyte in the polymer phase and in the gas phase is the coefficient K[14]:

$$K = \frac{c_{\text{poly}}}{c_{\text{gas}}} \tag{3}$$

where c_{gas} is the concentration of the analyte in the gas phase. By inserting Eq. (2) and Eq. (3) into Eq. (1), we have the following equation:

$$\Delta\omega \approx -\frac{1}{2}\frac{\omega_0 K V_{\text{poly}}}{m} c_{\text{gas}} \tag{4}$$

This is the measurement model of the gas sensor based on a polymer-coated microcantilever resonator. It can be seen that the concentration of the specific gas can be measured by detecting the resonant frequency shift of the microcantilever. The measurement is approximately linear.

1.2 Electrothermal driving mechanism

For the operation of the microcantilever resonator, a vibration driving and detecting mechanism is required. There are many mechanisms that have been successfully applied to micromachined resonant sensors[13]. When choosing an optimal scheme among the possibilities, in addition to the achievable driving forces and the required detecting sensitivities, production cost and reliability in the specific application environment also have to be considered. Table 1 lists the available driving and detecting schemes for microcantilever resonant sensors. The table displays the required components for each scheme, as well as the fabrication compatibility with IC technology.

Table 1 Driving and detecting schemes for microcantilever resonant sensors

Driving schemes	Detecting schemes	Required components	IC compatibility
Electrostatic	Capacitive	Input and output electrodes	Yes
Piezoelectric	Piezoelectric	Piezoelectric film with input and output electrodes	No
Magnetic	Inductive	Current coil and magnet	No
Electrothermal	Piezoresistive	Driving and sensing resistors	Yes
Electrostatic/piezoelectric/ magnetic/ electrothermal	Optical	Driving unit and laser source and detector	No

Vibration can be accurately detected by an optical level. Because the optical system is generally bulky and expensive, it is unsuitable for a sensor device. For compact sensor construction, integrated driving and detecting units are required. The microcantilever resonator examined in this paper integrates an electrothermal driving unit and a piezoresistive detecting unit with the microcantilever, but an optical detecting mechanism was also used in the experiments.

Figure 1 schematically shows the principle of the electrothermal driving microcantilever resonator. The driving signal, composed of a direct current (DC) component and an alternating current (AC) component, can be expressed by