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A real-time intelligent gas sensor system using a nonlinear dynamic response

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Abstract

We developed an intelligent gas sensor system for discrimination and quantification of gases by a single semiconductor gas sensor in real-time. This system is based on the information embedded in a nonlinear dynamic response. By applying a sinusoidal voltage to a heater attached to a sensing material, a characteristic time-dependent trace of the sensor resistance is obtained as a response to environmental gases. In order to evaluate the characteristic response in a quantitative manner, fast Fourier transformation (FFT) was performed for the dynamic response. Higher harmonics, obtained by performing FFT, were processed by using a discrimination method and a multiple regression. It is possible for the system to respond in the time order of several seconds. The physico-chemical meaning of the response was also discussed.

Keywords: Semiconductor gas sensor; Tin dioxide; Fast Fourier transform; Real-time system

1. Introduction

Oxide semiconductor gas sensors are widely used as an invaluable safety device due to the detection of methane, propane or carbon monoxide gas, at high sensitivity and low cost and because of their durability [1,2]. They are sensitive to most combustible gases, but unfortunately their selectivity is far from satisfactory.

To overcome this difficulty, there have been numerous attempts to construct a gas sensing system composed of several different types of gas sensors to analyze environmental samples, i.e. a so-called ‘multi-array’ sensing system [3]. The multi-array system can distinguish multiple samples, but it is not suitable for use as a semiconductor gas sensor because its composition and power consumption are prohibitively high. If each gas sensor exhibits a linear response to N different gases, one can identify and quantify the gases based on the algorithm of ‘linear transformation’ for the N-dimensional information matrix. However, this condition can never be achieved in reality because of the existence of nonlinearity between the input and output of the individual sensors.

In the past, there appeared several reports of a thermally cycled gas sensor to obtain several different sensitivity points [4,5]. In these attempts, the analysis was focused on almost stationary response at different temperatures. As a different approach, Nakata et al. proposed that time-dependent information is important for obtaining a higher degree of chemical information by using a nonlinear dynamic response from sinusoidal temperature change and analyzing the time sequence by FFT [6]. It is a superior method in terms of obtaining information from a sensor, since we can distinguish and quantify gases of eight species or each species separately in a mixed gas by using the response from a single sensor [7–10].

The maximum merits of the semiconductor sensors are easy to handle and respond quickly. However the merits were not capitalized upon in previous systems, because the method needed relatively large equipment such as measuring instruments and a high-speed processor and a long measurement period from 20 to 40 s. When applying the method to mobile robots or portable equipment for instance, these features represent huge disadvantages.

In particular, the feature whereby detection and quantification cannot be performed in real-time is a fatal flaw. In case of gas detection, a delay of about several seconds in not a problem from the viewpoint of real-time, because the flow and diffusion of a gas are relatively slow. However a longer delay will be crucial

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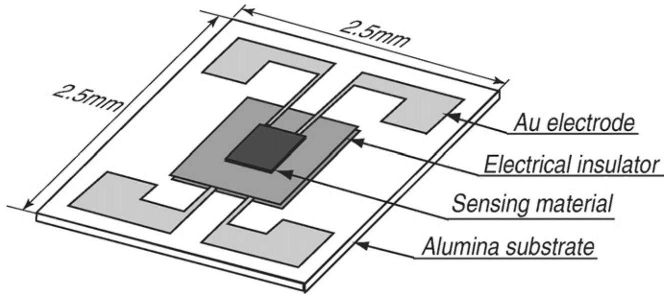

Fig. 1. Sensor structure of TGS-2400 gas sensor.

because the robot or equipment can move a certain distance during the delay.

In this paper, we present an intelligent real-time gas sensing system, which uses the dynamic nonlinear response of a semiconductor gas sensor. To realize the real-time feature of the system, we used a sensor that has a very small thermal capacitance [11,12] and a very punctual and flexible micro-controller embedded system [13]. Furthermore, this system is very simple, because it is combined with a commonly used personal computer and the universal serial bus (USB) interface.

2. Experimental

2.1. Fabrication of sensor

Fig. 1 shows the sensor structure. A glass layer for heat insulation was printed between the RuO_2 heater and an alumina substrate to reduce the amount of heat escaping toward the substrate. A pair of Au electrodes was formed on the thermal insulator. The gas sensing layer (0.5 mm × 0.5 mm) of SnO_2 doped with 1.5 wt.% Pt was printed on an electrical insulation layer and this was placed on the heater. Because the sensing layer and heater are so small, the heat capacity is markedly smaller than that of other types of sensors. This sensor can be heated up to from room temperature to 400 °C within 14 ms [11,12].

2.2. System configuration

To obtain high performance in terms of time accuracy and reliable data acquisition, we used a sensor module equipped with a micro-controller, which communicated with a personal computer (PC) via a USB interface. Fig. 2 shows a schematic diagram of the module that communicated with the PC. Both circuit voltage (VC) and heater voltage (VH) were controlled by the micro-controller with a switching transistor. By using the pulse width modulation (PWM) technique, VH can have any value between 0 and 5 V as the short time average value, while it can have only two values (0 or 5 V) at anyone time point. Because the period of PWM is short enough (51.2 μs) in comparison with the period of VH, we can assume that the VH value is slickly changing.

The time sequence of an applied voltage and measurement of sensor resistance is completely determined by the micro-controller, and the time accuracy of the sequence is very high. In order to achieve a wide range of sensor resistance (varying 100Ω–10MΩ range), the value was translated to the logarithmic one and stored in the micro-controller. The sinusoidal voltage change was continuously applied to the heater during working of the module.

In the next step, the stored data was transferred to the PC via the USB interface. A USB interface can transfer data at high speed (up to 1 M bytes s^{-1}) and it is required to clarify very complicated procedures. We used a dedicated controller chip for the USB (FT8U245AM manufactured by FTDI Ltd.). The stored data was sent to the PC continuously, and the application software on the PC processed the data and stored waveform and translated Fourier components [13].

2.3. Measurement set-up

For the sample gas, we used a 5.4-L chamber made of acrylic plastic. We attached a single sensor inside the chamber and connected the sensor with the module by a cable. The sample gas concentration was strictly regulated by direct injection of a calculated volume of a liquid sample inside the chamber. We tested several temperature and frequency conditions and noted that the conditions of 1 Hz and 1–4 V were the best for the discrimination under the system limitations. From a numerical simulation, we confirmed that the surface temperature was changing between 80 and 340 °C.

3. Results and discussion

3.1. Waveform and discrimination ability

Fig. 3 shows typical experimental traces of the resistance in control air and in the presence of ethanol and methanol gas for a sinusoidal change of the heater voltage. It shows the waveform

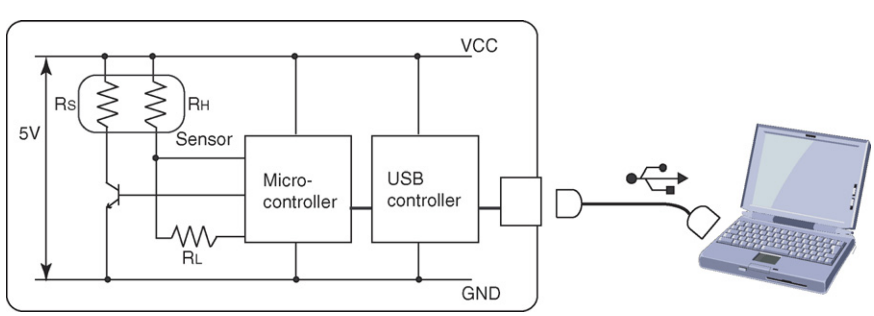

Fig. 2. Experimental circuit for detecting the dynamic response of a gas sensor.