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Redesigning Taguchi Sensor

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ABSTRACT

The configuration of the main components and the physical structure of the Taguchi sensor, the first ceramic gas sensor mass produced, has remained virtually unaltered since its appearance 40 years ago. This device owns an excellent combination of the quality factors but is non-selective. The research efforts carried out to enhance the selectivity in this resistive gas sensor are briefly reviewed. A novel design, Capillary-attached Gas Sensor (CGS), is introduced, which employs the same ceramic components used for the fabrication of a classical Taguchi sensor but in altered geometries. CGS presents remarkable advantages from the view point of selectivity over the original design. While the steady state response of a CGS has the same significance as that of the Taguchi sensor, its transient response presents valuable diagnostic information. Fabrication and test of a prototype CGS is reported.

Key words : Gas sensor, Taguchi sensor, Sensitivity, Selectivity, Gas diagnosis, Transient response, Steady state response

1. Introduction

The effect of the surrounding atmosphere on the electrical conduction in a semiconductor was first observed by W. H. Brattain and J. Bardeen on a single crystal germanium in 1953.[1] Useful gas sensing properties of thin film semiconductors were reported a decade later by T. Seiyama *et al.*[2] Taguchi patented his invention of oxide semiconductor-based gas sensor at nearly the same time,[3] and the mass production of his sensor started in 1968 by Figaro Co., Japan.

The device has an apparently simple structure, and operates based on the fact that the electrical conductivity of certain polycrystalline oxide semiconductors varies when they are exposed to a contaminated atmosphere. The contaminant reduces the adsorbed oxygen atom concentration at the surface of the oxide particles. Each oxygen atom leaves behind two electrons, which partially neutralize the surface charge on the particles and reduce the height of the potential barrier established between them. As a result, the conductance measured on a polycrystalline oxide semiconductor layer varies in accordance with the concentration of the contaminating gas; as the electronic conduction through the layer strongly depends on the height of the potential barrier established between the adjacent particles.[4]

The sensitive thick-film in the majority of the commercial devices is of tin oxide. SnO_2 is an n-type semiconductor, and hence, the response of the Taguchi sensor to a reducing Target Gas (TG) is in the form of a reduction in the resistance measured between the two ohmic contacts deposited on the oxide layer. The steady state response of the device to the presence of a contamination is related to both the concentration and the nature of the TG. The responses to a known pure TG can be calibrated and used for the measurement of the TG concentration levels. However, the device can hardly distinguish between two different TGs, A and B. Even if the device is more sensitive to A than B, it would hesitate in selecting a lower concentration of A or a higher concentration of B as the cause of its response. The situation is much more complicated when confronting the A-B mixtures. In these cases, a single Taguchi sensor will respond according to a nonlinearly weighted average of the effects of the gas components. In practical terms, and as is described below, this is all the information that a Taguchi sensor can provide regarding a contamination.

Meanwhile, Taguchi sensor owns a remarkable combination of positive quality factors. It is highly sensitive to most of the combustible and poisonous gases. It is compact, light, reliable and very cost effective; and it is easy to integrate it with the supporting electronic circuitry. This combination is the reason for the survival of this ceramic gas sensor, intact at its original configuration, in the competitive electronic component market for nearly half a century. The enhancements achieved during this period have been related to the optimization of the composition and microstructure of the gas sensitive oxide employed. These alterations, however, seldom targeted the physical design of the device.

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We have redesigned Taguchi sensor for selectivity enhancement. The design proposed, Capillary-attached Gas Sensor (CGS),[5-7] employs the same components as the classic version but in different geometries. In a CGS, while the steady state response has the same significance as that in the case of the classical design, the normalized transient response contains valuable information on the nature of the TG present. In this paper, after a brief review of the research efforts related to the selectivity enhancement in Taguchi sensors, the design and fabrication of a prototype CGS is reported. The test results presented indicate a remarkable selectivity.

2. Selectivity Enhancement

As described in the previous section, Taguchi sensor is non-selective. However, researchers have concentrated efforts on material modifications and optimizations to introduce some selectivity into the related chemical detection process. In this section a brief review of the results are presented. More details are given in thorough reviews of the subject.[8]

The sensitivity to a particular TG depends on the operating temperature of the sensor. This is due to the fact that both the adsorption and the desorption processes of the gaseous species to and from the surface of the gas sensitive ceramic are temperature dependent.[9] The temperature dependence of sensitivity to ethanol vapor, obtained for a tin oxide-based thin film resistive gas sensor is given in Fig. 1.[10] Although the main features of the sensitivity vs. temperature diagrams obtained for different TGs are similar but they are different in details. Then, if the operating temperature is varied by ΔT, the sensitivities to A and B would vary differently. The partial selectivity achieved in this way can hardly eliminate the cross-sensitivity to A and B but a plurality of identical sensors operating at different temperatures may present independent information regarding the nature of an unknown TG.

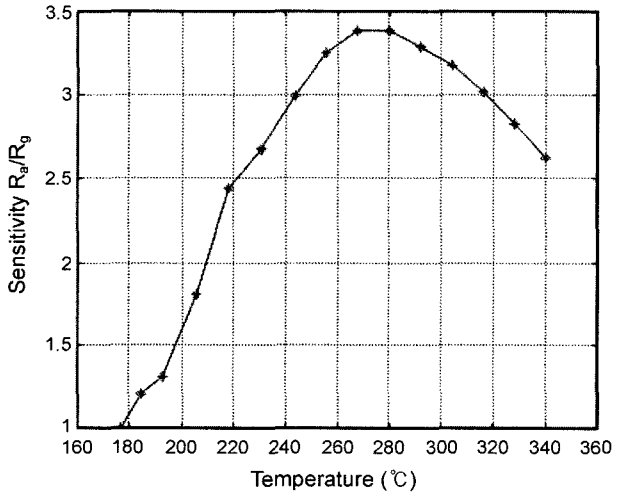

Fig. 1. The experimental relationship between the operating temperature of a tin oxide resistive gas sensor and its sensitivity to 2000 ppm of ethanol vapor in air.

Decoration of the effective surface of the sensitive oxide with a catalyst affects the sensitivity of the sensor to different TGs differently. Similar to the case of the operating temperature variations, the catalyst caused sensitivity alterations can technically be employed for partial selectivity enhancement in resistive gas sensors. The effects of Pt,[11,14] Pd,[11,14] and Ru[14] decorations on the sensitivity of Taguchi sensor to different TGs have been thoroughly studied. For instance, Ru decoration on tin oxide gas sensitive layers deposited by spray pyrolysis has increased the sensitivity to petroleum gas by an order of magnitude.[14] Decoration with a particular catalyst varies the sensitivity to various TGs in a specific manor; and information obtained from a number of identical sensors decorated by various catalysts may render selective detection.

Introduction of additives have also been considered for selectivity enhancement.[15,16] As an example, it has been shown that the addition of CuO to a SnO_2 layer makes it more sensitive to NO[17] and H_2S.[18] Others have used Cr and Co doping to reduce the interference of the humidity with the measurement of contaminants.[19] Addition of CaO and MgO is reported to increase the sensitivity to CH_4,[20] while MoO is said to improve the sensitivity to ethanol.[21] Some combinations of doping and decorations have also been tried : The selection between propane and methanol contaminations is reported to be facilitated by a combined In and Sb doping followed by a surface decoration by Pd.[22]

There are other alternative methods for selectivity enhancement. For instance, the variation of thickness and porosity of the sensitive film can affect the sensitivity to different TGs differently. The theoretical bases of the method have been analyzed by one of us.[23] The results indicate that different partial selectivities can be expected from identical sensors different only in the thickness of the sensitive layer or in the concentration of the micro-cracks present.

Possibilities for the creation of partial selectivity in resistive gas sensors are practically unlimited in number. However, the problem is encountered with our limited analytical knowledge regarding the actual process happening on the sensitive layer during the detection process. The introduction of further complications to the detection process would intensify the shortcoming mentioned, and of course, it would be hard to claim reproducibility, reliability, or durability regarding the selectivity enhancement techniques reviewed.

3. Redesigning Taguchi Sensor

The schematic diagram of a Taguchi sensor is shown in Fig. 2(a). It comprises a ceramic tube, a thick-film of the sensitive oxide deposited on the outer surface of the ceramic tube, two metal contacts to provide the ohmic connections to the sensitive oxide and a heating element which is located inside the tube to provide the elevated temperatures required for the optimum operation of the device.

Typical examples of the responses of a Taguchi sensor are presented in Fig. 3(a). These results have been recorded for a SnO_2-based resistive gas sensor fabricated and tested in

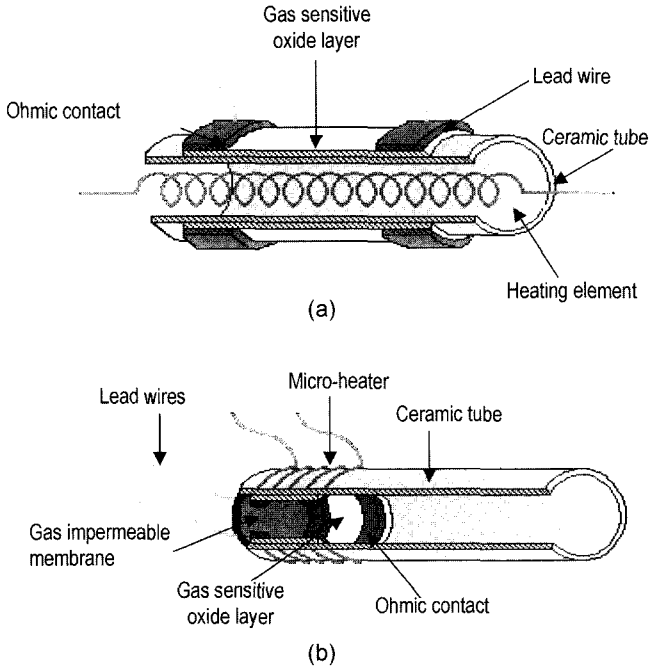

Fig. 2. Schematics of the classic Taguchi sensor (a) and the CGS design presented (b).

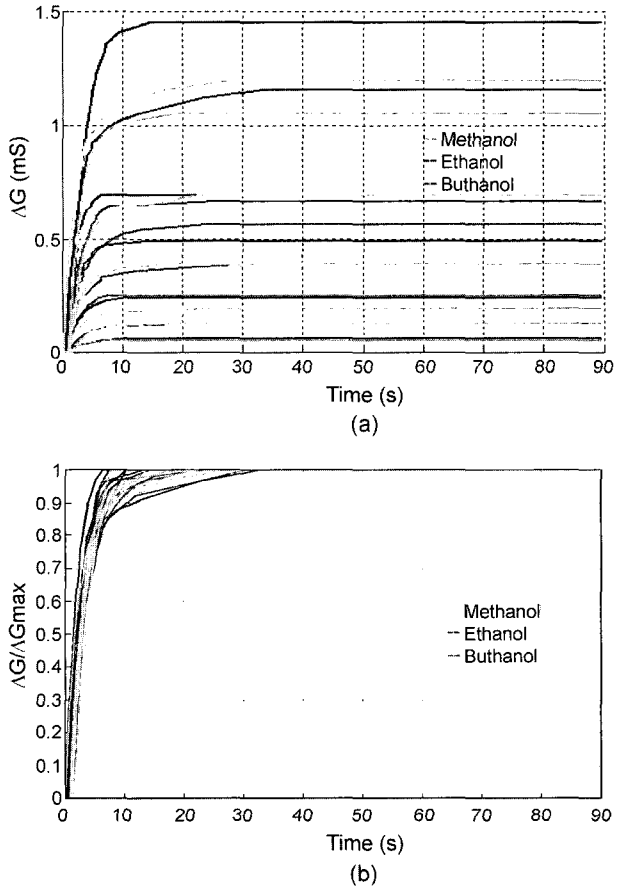

Fig. 3. Responses of a Taguchi sensor to three different pure target gases varying in the concentration range of 80-10,000 w-ppm (a). The same, after normalization (b).

our laboratories. Confronting the contaminated atmosphere at $t = 0$, the conductivity of the sensor has increased with time to reach a steady state value in about 10 s. The temporal variation of the response in the $t = 0 - 10$ s is referred to as the transient response of the sensor, while the approximately constant response level beyond $t = 10$ s is defined as the steady state response or simply "the response" of the sensor.

According to the results presented in Fig. 3(a), the sensitivity of the sensor to ethanol is higher than the other contaminants examined. The observed partial selectivity of this sensor to ethanol, however, can hardly facilitate acquisition of any information regarding the ethanol content in a mixture of the three vapors examined. With a similar reasoning, it can be concluded that none of the above reviewed techniques could render diagnostic ability to a single Taguchi sensor, and the steady state response of the sensor is hardly of any potential in this respect.

In order to investigate the diagnostic potentials of the transient response, it is beneficial to extract their most vivid feature related to the concentration of the target gas. All of the responses depicted in Fig. 3(a) are presented in Fig. 3(b) after normalization. The normalization factor, in each case, is the maximum response level attained for the TG related, i.e. the steady state of that particular response. The normalized transient responses resulted for different TGs are practically indistinguishable. At the present state of the art, the minor differences among the different normalized transient responses can disappear behind the fluctuations resulting from the instabilities related to the operating point, recording conditions, secondary effects of TG concentration and gradual degradation of the device. It is, hence, concluded that even though the transient response contains some diagnostic information but the extraction of this information is presently impractical.

The novel design concept is presented in Fig. 2(b), where it can also be compared with the classic structure of Taguchi sensor (Fig. 2(a)). The main components of the two designs are the same. The ceramic tube is longer, and the geometrical positions of the sensitive oxide layer and the heating element have changed. The SnO_2 thick-film has been deposited inside the tube, while the heating element is located in a proper position outside the tube. The schematic diagram of the prototype fabricated based on the CGS concept is presented in Fig. 4. A

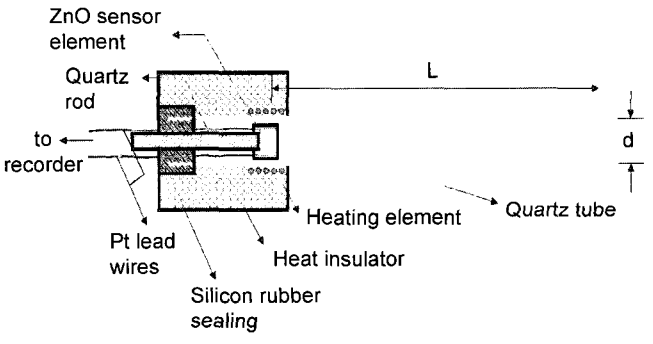

Fig. 4. Schematic diagram of the prototype CGS fabricated.

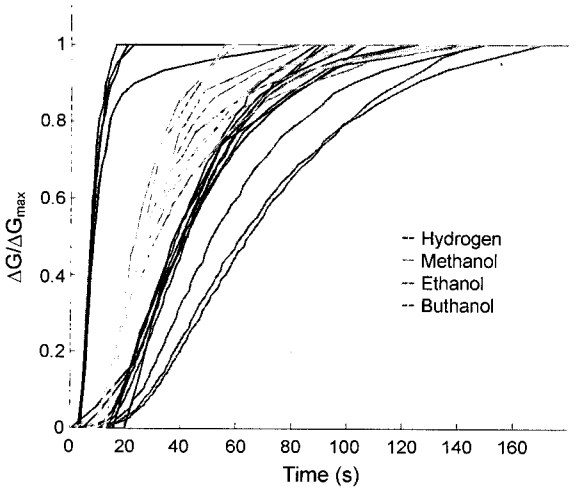

Fig. 5. Normalized transient responses of the prototype CGS to hydrogen, methanol, ethanol and butanol. The different traces, in each case, are related to the different concentrations of the contaminant.

segment of quartz capillary was employed instead of the commonly used alumina-based tube. The gas sensitive element employed was of ZnO. The porous ZnO body was formed by different techniques[24] on two segments of platinum wire, which provided the ohmic contacts required. Further details of the assembled prototype are presented elsewhere.[7]

4. Test Results

The open end of the prototype CGS was inserted into a gas chamber. The moment of insertion was defined as $t = 0$. The temporal variation of the electrical conduction of the gas sensor element was recorded for different contaminated atmospheres. The concentrations of methanol, ethanol and butanol were varied in the range of 80-10,000 w-ppm. Hydrogen was listed among the contaminants as a reference, as it should create the fastest response possible. The data obtained were normalized as described in the previous section. The normalized transient responses are presented in Fig. 5. The responses to different TGs have occurred in different times as the CGS responds faster to the TG of higher diffusion coefficient. The diagnostic abilities of the device are obvious. An electronic data processing system could select the response of an unknown TG, among the four pure target gases examined on time-based calculations.[7]

The results verify the CGS theory presented elsewhere.[5]

5. Conclusion

The techniques applied for obtaining partially selective sensitivity in resistive gas sensors were briefly reviewed. It was shown that the achievement of gas diagnosis based on these methods and using a single Taguchi sensor is difficult if not impossible. A novel design for Taguchi sensor was presented. Although the device employs the same components as the classic design but operates on entirely different principles. The fabrication of a prototype CGS was described. The test results indicated a remarkable time-based selectivity regarding the pure target gases examined.

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