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Power reduction with enhanced sensitivity for pellistor methane sensor by improved thermal insulation packaging

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ABSTRACT

The pellistor (catalytic combustion) methane sensor is a typical sensor with high working temperature. Historically, its heat dissipation via packaging has not been fully considered for power minimization. A large amount of thermal energy from the pellistor sensor is typically lost to the environment because of the sensor's high sensing temperature and quasi-closed metal packaging. A promising new approach to minimize the sensor power budget will be developed when part of this heat energy is successfully retained. In this paper, we explore this possibility by introducing hydrophobic silica aerogel as packaging material owing to its excellent low thermal conductivity and high gas permeability. Experimental results reveal that a significant power decrease of approximately 30% and high sensitivity can be simultaneously achieved for the traditional active pellistor methane sensor with thermal insulation-strengthened packaging with silica aerogel.

1. Introduction

Methane is an odorless, colorless, dangerous gas with a Lower Explosive Limit (LEL) and an Upper Explosive Limit (UEL) concentration of approximately 5% and 15%, respectively, by volume in air [1]. Coalmine methane has been perceived as a serious hazard to underground coalmines for hundreds of years. In terms of safety, real-time and universal detection of methane accumulation is important in coalmines, as well as in other closed environments such as landfills. With benefits of higher nodal densities and lower installation costs [2], Wireless Sensor Networks (WSNs) are very suitable for safety supervision of underground coalmines. However, methane sensors block WSN application in coalmines. Although various methane sensors have been proposed based on different sensing principles [1,3] (e.g., semiconductor gas sensors, optical sensors, thermal conductivity sensors, and electrolyte sensors), no satisfactory methane sensor has been developed that can fully meet wireless sensor demands in coalmines. The primary methane sensors used in coalmines are pellistor (catalytic combustion) methane sensors and Non-Dispersed Infrared (NDIR) methane sensors. Owing to the high cost and difficulty in avoiding water vapor condensation, the NDIR methane sensor is inadequate in meeting the needs of wearable and portable facilities for WSNs. Pellistor is a reliable and cost-effective gas sensor that has successfully been used for detection of explosive gases in mines and other high-risk areas for over fifty years and will remain in use for timely detection of methane [4]. In terms of practical application in coalmines, the catalytic combustion gas sensor might be the most promising candidate for WSN. However, one major challenge for the pellistor methane sensor in WSNs is its high power consumption, which typically ranges from 200 mW to 600 mW. Work with catalytic combustion sensors has mainly focused on Si or LTCC (low temperature co-fired ceramics) micro-machining [5–9] because dimension miniaturization is the traditional approach to decreasing power consumption. Unfortunately, power consumption reduction of the micro-combustion methane sensor is generally accompanied by unacceptable sensitivity.

The working temperature of pellistor is quite high at approximately 400 °C. Under this high-temperature working condition, the heat loss from pellistor to environment becomes one major reason for the high power consumption of pellistor and short battery life, because air conduction is a dominant heat transfer mechanism even for micro-heating devices [10–12]. However, few studies have investigated the packaging of gas sensors. Norman et al. published a report on the experimental effect of macro-flow cell packaging configuration on the response of catalytic micro-heater gas sensors [13]. Gmür et al. studied the power consumption dependence of a gas sensor microarray on flow rates with numerical simulation and experiments [14]. To the best of our knowledge, no effective thermal isolation packaging solution is available for pellistors. In this paper, we attempt to reduce power consumption by using improved thermal insulation packaging with aerogel. Aerogel was

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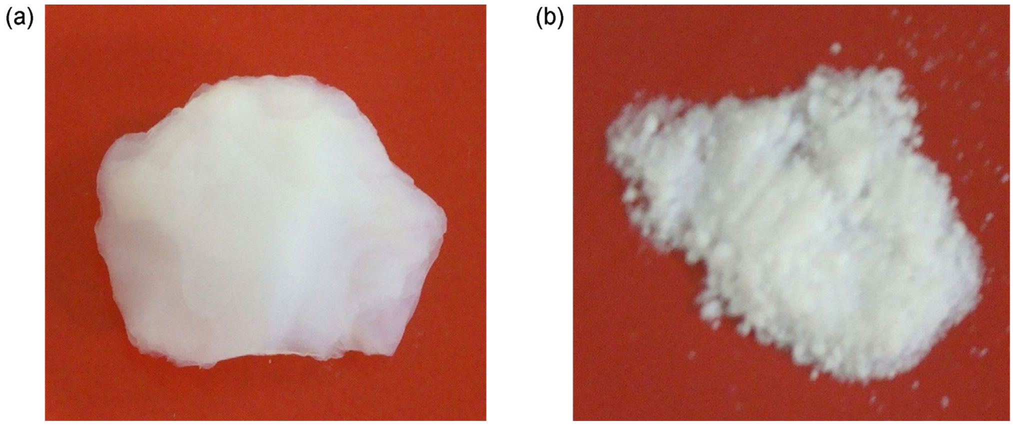

Fig. 1. Images of hydrophobic silica aerogel and nano-silicon powder, (a) a piece of hydrophobic silica aerogel, and (b) nano SiO_2 powder.

chosen because of its remarkable open-cell porosity structure and inherent characteristics (e.g., high specific surface area, low density, ultra low dielectric constant, and excellent heat insulation properties) [15–17]. Significant research has been devoted to its applications because of these distinctive properties. Aerogel is used in high-speed electronic devices as a low-k dielectric material [18]. Owing to its high surface area, aerogel has been adopted in some biological and environmental sensors [19–21]. As a super-thermal-insulating material, aerogel has been demonstrated in a variety of microsystems [22–25]. In this paper, we mainly focus on the application that leverages its thermal properties for packaging pellistor sensors.

2. Material and experiments

2.1. Silica aerogel and aerogel characterization

The preparation of hydrophobic silica aerogel has been described elsewhere in detail [17,26]. Generally, its synthesis is divided into three steps: preparing the gel, aging the gel, and drying the gel by means of supercritical or ambient pressure methods. In this study, hydrophobic silica aerogel was selected to avoid the destruction of the nanostructure of silica aerogel by the water vapor [16,27] from the oxidation combustion of methane. The hydrophobic silica aerogel was purchased from Yingde Alison Asia Pacific Electron Co., Ltd. Considering the same chemical composition and relatively low thermal conductivity, SiO_2 nanopowder was also used as a contrast material. Fig. 1 shows the pictures of hydrophobic silica aerogel and nano-silicon powder.

Fig. 2 depicts a water droplet that was placed on the surface of a piece of hydrophobic aerogel. The water contact angle was measured to be approximately 136°, which indicates that the silica aerogel is super hydrophobic. With such perfect hydrophobic, uneven surface and super-low density, a piece of silica aerogel can float on the water surface and automatically moves from place to place under its own gravity. The surface morphology and microstructure of the hydrophobic silica aerogel was also investigated via scanning electron microscopy and transmission electron microscopy as shown in Fig. 3(a) and (b), respectively. Silica nanoparticles can be clearly observed clustering together to form a porous structure.

2.2. Experimental setup

The typical packaging of traditional pellistor is the modified semiconductor TO packaging, which comprised a cylindrical metal cap and a metal or isolate base with pins. Conventionally, a hole should be opened to allow methane entering and thus reacting with the pellistor sensing materials, as shown in Fig. 4(a). Simultaneously, to provide suitable thermal insulation that would prevent excessive heating energy loss, the heated element (bead) was simply suspended within the packaging by pin bonding, as indicated in Fig. 4(b).

Our experiments were performed with commercial pellistor, as shown in Fig. 4. To evaluate the thermal insulation improvement effect, the TO package of pellistor was fully filled with powder of hydrophobic silica aerogel and SiO_2, respectively. The bead and the pins in the packaging were thus all encapsulated by aerogel or SiO_2 powder.

The electrical properties of the pellistor are studied in constant current mode. The corresponding voltage was recorded when the thermal steady-state condition was reached with current variation from 10 mA to 90 mA, mainly in 2-mA increments. Finally, the methane response of the active pellistor was investigated with several different standard low-concentration methane mixtures in air.

3. Results and discussion

3.1. Electrical response

Fig. 5 depicts the current–voltage (I–V) characteristics in static pure air of the active pellistor, respectively, in the traditional TO gas packaging and the modified TO metal packaging that filled with silica aerogel and nano-silicon. Compared with the pellistor in traditional packaging, the pellistors in the nano-silicon- and

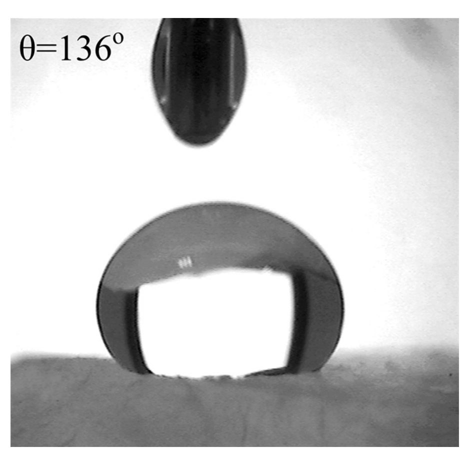

Fig. 2. Hydrophobicity of silica aerogel. The contact angle of a water drop on a piece of silica aerogel was measured to be 136°.