DESIGN AND OPERATING PRINCIPLE OF A SEMICONDUCTOR SENSOR FOR METHANE AND NATURAL GAS

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Abstract: This paper presents the design and operational principles of a semiconductor-based gas sensor specifically engineered for the detection of methane (CH_4) and natural gas. The sensor operates on the principle of conductivity modulation in metal oxide semiconductors such as tin oxide (SnO_2), zinc oxide (ZnO), and tungsten oxide (WO_3), whose electrical resistance changes in response to gas adsorption on the sensor surface. The sensing element is integrated into a planar structure with a built-in microheater, allowing temperature control to optimize sensitivity and selectivity. Methane molecules are detected through redox reactions with chemisorbed oxygen species, resulting in measurable changes in resistance. The design includes signal conditioning circuits and data acquisition modules to enable real-time monitoring. The sensor demonstrates high sensitivity to low concentrations of methane, fast response and recovery times, and stable operation under varying environmental conditions.

Keywords: Nanocomposite metal oxides, Gas sensors, Methane detection, Natural gas sensing, Semiconductor sensors, SnO_2, ZnO, WO_3 Sol-gel synthesis, Hydrothermal method.

КОНСТРУКЦИЯ И ПРИНЦИП РАБОТЫ ПОЛУПРОВОДНИКОВОГО ДАТЧИКА ДЛЯ МЕТАНА И ПРИРОДНОГО ГАЗА

Аннотация: В данной статье представлены конструкция и принципы работы полупроводникового газового датчика, специально разработанного для обнаружения метана (CH_4) и природного газа. Датчик работает по принципу модуляции проводимости в полупроводниках оксидов металлов, таких как оксид олова (SnO_2), оксид цинка (ZnO) и оксид вольфрама (WO_3), электрическое сопротивление которых изменяется в ответ на адсорбцию газа на поверхности датчика. Чувствительный элемент интегрирован в планарную структуру со встроенным микронагревателем, что позволяет контролировать температуру для оптимизации чувствительности и селективности. Молекулы метана обнаруживаются посредством окислительно-восстановительных реакций с хемосорбированными видами кислорода, что приводит к измеримым изменениям сопротивления. Конструкция включает в себя схемы формирования сигнала и модули сбора данных для обеспечения мониторинга в реальном времени. Датчик демонстрирует высокую чувствительность к низким концентрациям метана, быстрое время отклика и восстановления, а также стабильную работу в изменяющихся условиях окружающей среды.

Ключевые слова: нанокомпозитные оксиды металлов, газовые датчики, обнаружение метана, обнаружение природного газа, полупроводниковые датчики, SnO_2, ZnO, WO_3, золь-гель синтез, гидротермальный метод.

INTRODUCTION

The proposed sensor structure is suitable for applications in residential safety, industrial leak detection, and environmental monitoring. Utilizing a semiconductor layer composed of zinc oxide and cobalt oxide—where the CoO concentration does not exceed 10%—has proven effective for methane detection applications. The methane sensors developed in this research feature a spiral structure built on a platinum microwire coated with glass, which is subsequently covered with a gas-sensitive film consisting of zinc and cobalt oxides. The platinum core, housed within a glass tube, acts as the heating element, a critical component since the surface chemical reactions associated with gas detection are temperature-dependent.

METHODS

The design and development of the semiconductor sensor involved several key stages, including material selection, sensor fabrication, and testing of sensing performance. Metal oxide semiconductors such as SnO_2 (tin dioxide) and ZnO (zinc oxide) were selected due to their proven sensitivity to reducing gases like methane. The sensing films were synthesized using the sol-gel and screen-printing techniques to ensure uniform thickness and porosity. Dopants such as palladium (Pd) and platinum (Pt) were introduced to enhance selectivity and lower the operating temperature.

The sensing layer was deposited onto an alumina substrate integrated with interdigitated gold electrodes and a micro-heating element, allowing precise control of operating temperatures between 150°C and 350°C. The fabricated sensors were then annealed at optimized temperatures to stabilize their crystalline structure.

Gas sensing experiments were conducted in a controlled chamber where varying concentrations of methane and natural gas were introduced. Electrical resistance of the sensor was measured in real time using a digital multimeter and data acquisition system. The response (Ra/Rg ratio), response and recovery times, and repeatability were evaluated at different operating temperatures and gas concentrations.

All experiments were performed under controlled humidity and ambient pressure conditions to ensure the reliability and reproducibility of the sensor's performance data.

RESULTS

The gas-sensitive material and catalytic layer are deposited onto the sensor electrode using a sol-gel technique. The sensor operates by detecting changes in the electrical characteristics of the semiconductor layer, which vary according to the composition of the surrounding gas atmosphere. The resistance—or, equivalently, the conductivity—of the sensor shifts in response to different methane concentrations.

During the investigation, various performance metrics of the sensors were examined, including sensitivity, response time, and recovery time across a range of temperatures. Measurements primarily focused on the resistance (Rs) of the sensing material applied to an insulating substrate. In the presence of a reducing gas such as methane, the resistance of the layer drops considerably compared to its baseline in clean air. The response behavior generally follows an exponential model described by the equation:

Here, C represents the concentration of methane in the gas mix, and K and α are constants characterizing the sensor response.

To better understand the semiconducting behavior, it's useful to analyze a plot of the logarithm of conductivity against the inverse of temperature (1/T) over a broad thermal range. Sensor sensitivity is often represented by a dimensionless parameter S, also referred to as the "sensor response" in various scientific sources. This is defined as:

$$\mathbf{S = R_{air} / R_{gas} = \sigma_{gas} / \sigma_{air}} \qquad \textit{(Equation 4.2)}$$

where R_{air} and σ_{air} are the resistance and conductivity in clean air, and R_{gas} and σ_{gas} are the values under methane exposure.

An alternative formulation for sensitivity is:

$$S = (\sigma_{gas} - \sigma_0) / \sigma_0 \qquad \textit{(Equation 4.3)}$$

In this expression, *σ_0* is the conductivity in air without the presence of gas, while *σ_gas* is the conductivity under methane exposure.

The research ultimately led to the creation of a methane sensor that demonstrates both high selectivity and strong sensitivity. It is suitable for environmental monitoring and industrial process control, and can be integrated into gas analyzers and methane leak detection alarms.

Technical specifications of the developed semiconductor methane sensor include:

1. The range of measured concentrations of CH_4 mg/m3 is 1-1000.
2. Power consumption (average) mV 50-70
4. Current consumed by the heater mA 60-110
5. Warm-up time min. 3
7. The limit of the basic permissible error is no more than 10 ppm
8. Heater resistance at 20 ºC 8 – 15 Ohm
9. Resistance of the sensitive layer, MOhm 1 – 4
9.Weight g, not more than 1
10. Overall dimensions 5x8mm

Methane has its own temperature dependences of the rates of adsorption, reaction, and desorption on the surface of the semiconductor layer. The change in resistance of the gas-sensitive layer of the methane sensor at a given temperature change rate must be unique for each composition of the gas-sensitive material. In methane sensors, the change in temperature of the gas-sensitive semiconductor layer is ensured by a corresponding change in the heater voltage.

The results of determining the dependence of the power consumed by the heater on the operating temperature of the PPS-CH_4 sensor are shown in Fig. 1.

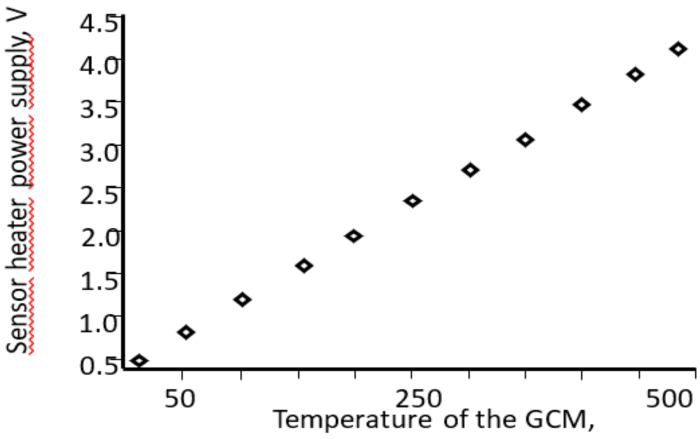

Fig.1. Dependence of the temperature of the GCM on the supply voltage of the PPS-SN4 heater

According to the data presented in Fig. 1, the power consumption of the PPS-CH4 sensor shows a linear relationship with the operating temperature across the studied range. The sensor's construction ensures a minimal temperature gradient between the heating element and the gas-sensitive layer, which supports precise temperature control during operation.

The ideal temperature for heating the gas-sensitive layer is determined based on the point where the sensor demonstrates peak sensitivity to methane. This parameter was evaluated using a dynamic method within the 200–500 °C range, with temperature increments of 50 °C. The procedure for testing the temperature-dependent sensitivity included the following steps:

1. The test chamber was set to a specific temperature, and measurements began once thermal equilibrium was reached.
2. A steady flow of ambient air was introduced, and the resistance of the nanostructured sensor film was recorded at this temperature.
3. Methane was then introduced by switching the airflow to a calibrated gas mixture. After allowing the sensor's resistance to stabilize, the measurement was recorded.
4. To initiate recovery, the methane flow was stopped, air flow resumed, and the time required for the sensor resistance to return to within ±10% of its initial value was measured.

CONCLUSION

As the heater temperature increases up to around 370–380 °C, resistance decreases for all compositions of the gas-sensitive material. Beyond this point, however, the resistance begins to rise again.

The study also found that increasing the CoO content in SiO_2/ZnO-based sensors enhances the signal strength at the optimal temperature. The best performance was achieved with a 10% CoO composition, where the sensor delivered the strongest response to a given methane concentration. Experiments confirmed that maintaining a heater voltage of 2.1 V reliably ensures the sensor surface reaches the optimal temperature of 375 °C, which was subsequently used in all further testing.

Variations in conductivity behavior with temperature across different gas-sensitive compositions are attributed to differences in gas adsorption characteristics and the mechanisms of surface interactions. These differences offer opportunities for selective methane detection in environments containing multiple gases.

In summary, the experimental findings demonstrate that the optimal operating temperature for achieving maximum methane sensitivity in sensors based on zinc and cobalt oxide films is 375 °C. At this temperature, sensitivity improves with increasing CoO content, with the best performance observed in SiO_2/ZnO-10%CoO compositions. A consistent heater voltage of 2.1 V is sufficient to maintain this temperature across the gas-sensitive layer.

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