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Using Field-Effect Gas Sensors for Monitoring H_2 in Transformer Oil

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Abstract. Hydrogen can be released during the thermal decomposition of organic materials, therefore, monitoring its level in the working industrial high-voltage transformer oil allows you to identify the development of degenerative processes in advance, because these processes can lead to an accident in the future. In experiments has shown that highly sensitive and small-sized field effect gas sensor based on the metal-insulator-semiconductor structure can be used for measuring of Hydrogen in oil with direct contact of its structure with transformer oil. Given the harsh environmental conditions of hydrogen measurement the field effect capacity type gas sensor were fabricated by using laser micromilling technique for fabrication compact ceramic surface mounting device package and microheater for sustentation working temperature of metal-insulator-semiconductor structure.

1 Introduction

Transformers are one of the main components of the complex equipment of many energy (power plants, substations, converting devices) or industrial enterprises. In order to avoid equipment failure, it is necessary to conduct transformer oil tests in a timely manner. More precisely, a check is made of its quality. Periodic monitoring of transformer oil is one of the components of technological maintenance of industrial equipment in enterprises. The main characteristics of transformer oil, its purity and useful properties determine the performance of transformers. The ability of the oil to maintain its original properties in operating equipment during operation is called the stability of transformer oil. If the power equipment has no defects and works without failures, then the characteristics of the new oil practically do not change. Fresh transformer oil has a light color and certain conforms to certain standards that determine its dielectric and physico-chemical properties. During operation, the stability of transformer oil is significantly reduced, noticeable changes in performance appear and the oil darkens.

The quality tests determine the start of the aging process of transformer oil. Based on the tests of transformer oil, its performance is assessed, the necessary cleaning and recovery procedures are prepared, and comprehensive reports on the overall operational status of the transformer equipment are prepared [1]. In transformer oil, it undergoes a thorough analysis due to the fact that water and air are one of the main catalysts for the aging process of working fluids. Moisture content is measured by the amount of hydrogen in the interaction of transformer oil with calcium hydride for a specified time [2]. The gas content is calculated using an absorbiometer [3], Fourier transform infrared spectroscopy [4] or chromatograph [5].

Hydrogen can be released during the thermal decomposition of organic materials; therefore, monitoring its level in the working industrial high-voltage transformer oil allows you to identify the development of degenerative processes in advance, because these processes can lead to an accident in the future. In experiments has shown that highly sensitive and small-sized field effect gas sensor based on the metal-insulator-semiconductor (MIS) structure can be used for measuring of H_2 in oil with direct contact of its structure with transformer oil. Numerical estimates show that with the diffusion coefficient D = 4*10-9 m^2/s [6] (at room temperature), the time required for H_2 saturation in a transformer oil with 10 cm depth to a level $0{,}9C_0$ is more than 1 year. In reality, there are convective flows occurred due to the temperature gradient which are combined with diffusion. Nevertheless, such a large diffusion time must be taken into account when designing the experimental setup and the obtained results interpreting.

2 Experimental

A schematic representation of the field-effect gas sensor is shown on Figure 1 and described in work [7]. The measuring H_2 concentration with the field-effect gas sensor is as follows. When hydrogen molecules from the external environment interact with the metal electrode, H_2 molecules decompose into atoms and diffuse to the

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metal-insulator interface. It is known that on the surface of palladium hydrogen atoms have a dipole moment. The electric field of dipoles leads to a change in the electric field in the dielectric and in the surface layer of the semiconductor. As a result, the capacitance of the MIS-structure changes, the value of which is fixed by the electronic unit while maintaining a constant bias voltage on the MIS-structure.

Given the harsh environmental conditions of hydrogen measurement the field effect capacity type gas sensor were fabricated by using laser micromilling technique for fabrication compact ceramic surface mounting device package and microheater for sustentation working temperature of MIS structure. The technology of fast fabrication functional sensor in specific ceramic SMD package with base 9x9 mm was precisely described in work [8] and photo of sensor package is shown on Fig. 1. A significant problem remains the difference in the energy consumption of sensors located in the air and immersed in transformer oil due to the difference in the thermal conductivity of mediums. The use of ceramics for the manufacture of the sensor package not only reduces the overall size of the sensor, but also allows to reduce this dependence on the thermal conductivity of the ambient medias in comparison with the use of standard metal casings for gas sensors used by us in other our works where it is more important for selectivity and decrease time of sensor response [9-10].

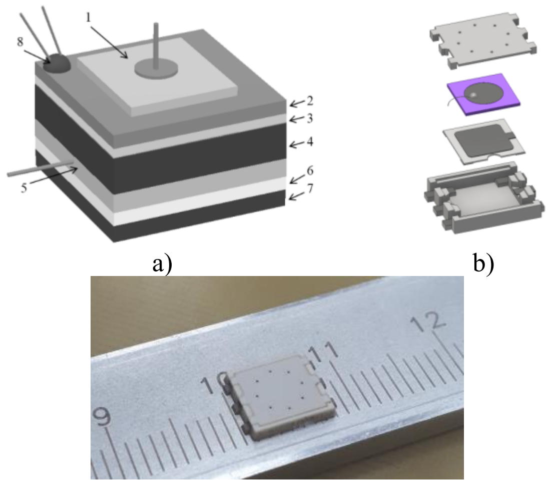


Fig. 1. Schematic representation structure of field-effect gas sensor in SMD package. (a) MIS-structure, which is a capacitor, the substrate of which is an n-type silicon wafer (4), 3 - coated on one side with a SiO_2 film and 2 - an additional layer of Ta_2O_5; 1 - catalytic metal Pd film is applied to the dielectric by laser sputtering, to which an external metal electrode is glued; 5 - the second electrode is glued to the metal layer deposited on the back of the capacitor (semiconductor); 6 - the MIS-structure is located on the insulating plate, 7 - separating it from the film resistive heater. 8 - the temperature of the sensitive element is measured and adjusted with a thermistor. (b) 3D model of package and microheater in *.stl format (screenshot in the Autodesk Inventor CAD program) before ceramic package fabrication (c) External view already assembled MIS sensor in SMD package (dimensions scale are in mm).

The sketch of setup used in experiment imitates similar to a transformer conditions of H_2 diffusion present on Fig. 2. Both field-effect sensors were preliminarily calibrated for H_2 in air (in the concentration range 5-100 ppm) at the sensing element temperatures of 23 and 100°C. The optimal temperature of the sensor structure is 100-150°C. The total capacity of the tank used in experiments is 1 liter, and the volume of transformer oil used is 0.1 liter. The height of the oil column is 2 cm.

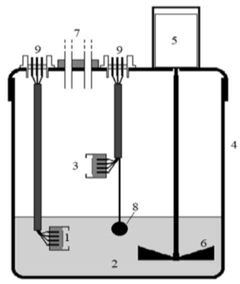


Fig. 2. Schematic representation of the experimental setup: 1 - the main field-effect sensor; 2 - the structure of the sensitive element of which interacts with transformer oil; 3 - the reference field-effect sensor, located in the air gap above the oil, are placed in 4 - an airtight container; 5 - the electric motor rotates for 6 - the mixing device; 7 - the tubes are used to supply the specified concentration of hydrogen and ventilation of the container; 8 - the temperature of the oil is controlled with a thermocouple; 9 - vacuum electrical connectors are used for electrical input.

In Table 1 measurement results of the field-effect sensor sensitivity to hydrogen in air and in transformer oil are presented. S – concentration sensitivity H_2 5 ppm; A_n– signal noise amplitude ;$\tau_{0,9}$ and $\tau_{0,1}$ signal saturation time to a level of 0.9 at H_2 concentration of 5 ppm and signal relaxation time to a level of 0.1 from a signal recorded at 100 ppm; T_{sensor} – sensor working temperature.

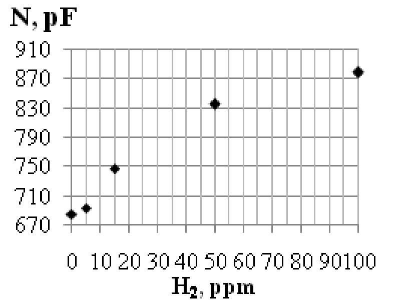
Table 1. Measurement results of the field-effect sensor sensitivity to hydrogen in air and in transformer oil.

Parameter	In air	In oil	T_{sensor}, °C
S, pF/ppm	5,2	2	23
A_n, ppm	0,4	0,8	
$\tau_{0,9}$, hour	5,5	5,9	
$\tau_{0,1}$, hour	10	>12	
S, pF/ppm	5,5	-	100
A_n, ppm	0,3	-	
$\tau_{0,9}$, min	8	-	
$\tau_{0,1}$, min	17	-	

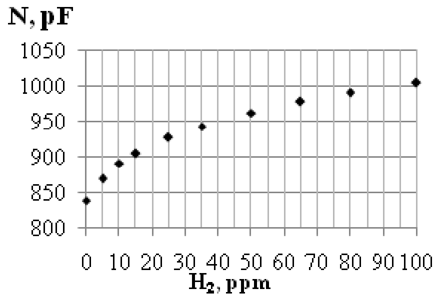
3 Results and Discussion

During experiments, we have target the using main sensor under ambient temperature for excluding excess power consumption for maintaining working temperature in intense heat exchange with oil. For this reason, its heating element was turned off and equal to the temperature of the oil and was 23°C. The reference sensor was maintained at a temperature of 100°C. Relative humidity above oil was 25%. The experiment was carried out as follows. Through drainage tubes, fixed H_2 concentrations in the range from 5 ppm to 100 ppm were fed into the container. After the mixture was supplied, the tubes were blocked and, subsequently, the H_2 concentration in the vessel was monitored by sensor (Fig. 2, position 3).

To accelerate the process of oil saturation with H_2, a mixing device was used, the rotation frequency of which was selected to exclude the formation of air bubbles in the oil. Figure 3 shows the dependence of the response of the sensors (main and reference) on the concentration of H_2. Table 1 shows the measurement results.



a)



b)

Fig. 3. The static characteristics of the field-effect sensor are: (a) the structure of the sensor (working temperature 23°C) is in contact with transformer oil, (b) the structure of the sensor (working temperature 100°C) is in contact with air.

The experiment showed that the temperature of the sensor has a significant effect on the detection time of H_2. Immersion of the sensor in oil leads to an increase in the noise level of the signal and a decrease in the sensitivity of the sensor in the low concentrations range. Also, the presence of transformer oil does not change the functional dependence of the sensor capacity on the H_2 concentration. The response time to H_2 is significantly less than the time of its diffusion in oil, which makes it possible to use the sensor as a sensitive element in the control systems for the level of dissolved H_2 in the oil of a working transformer under ambient temperature.

4 Summary

It has been demonstrated that by using laser micromilling technology possible to fabricate custom integrated microheater platform with SMD package for MIS gas sensor. The design is based on monolithic ceramics, the use of platinum as the material of the heater and the thermometer creates a mechanically robust design that is resistant to aggressive transformer oil media. Practical experiments have shown that for the sensitivity of the sensor, the difference in the composition of the gaseous medium and hydrogen dissolved in oil is negligible. From a physical point of view, the difference in energy consumption and operating temperature is manifested in the response rate to hydrogen, which differs by 35 times for air and oil, respectively. Since the rate of increase in the concentration of hydrogen in the transformer oil relative to the sensor response time is small, it is preferable to use the sensor at ambient temperature without exposing it to unnecessary temperature stresses and unreasonably excessive energy consumption. The developed design of field-effect sensor can be used as an inexpensive tool for on-line monitoring quality of transformer oil, without resorting to alternative expensive analyzes.

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References

1. W.H. Tang, Q.H. Wu, Springer, London (2011)
2. V. V. Kondalkar, G. Ryu, Y. Lee, K. Lee, Sensors and Actuators B: Chemical, **286** 377-385 (2019)
3. Y. Gui, W. Li, X. He, Z. Ding, L. Xu, Applied Surface Science, **507** article 145163 (2020)
4. J. Jiang, Z. Wang, G. Ma, H. Song, C. Zhang, Optik, **176** 214-220 (2019)
5. Y. Leblanc, R. Gilbert, M. Duval, J. Hubert, Journal of Chromatography A, **633** 185-193 (1993)
6. A.L. Bychkov, S.M. Korobeynikov, A.Y. Ryzhkina, Technical Physics, **56** (2011) 421-422
7. I.N. Nikolaev, L.N. Kalinina, A.V. Litvinov, Automation and Remote Control, **72(2)** 442-448 (2011)
8. N. Samotaev, A. Litvinov, M. Etrekova, K. Oblov, D. Filipchuk, A. Mikhailov, Sensors, **20(5)** article 1514 (2020)
9. B. Podlepetsky, M. Nikiforova, A. Kovalenko, Procedia Engineering, **168** 251-254 (2016)
10. B. Podlepetsky, N. Samotaev, M. Nikiforova A. Kovalenko, Sensors, **19(8)** article 1855 (2019)