Sensors and Actuators B 223 (2016) 520–526

Contents lists available at ScienceDirect

Sensors and Actuators B: Chemical

journal homepage: www.elsevier.com/locate/snb

Review Article

Hydrogen effect on density and Young's modulus of thin films in acoustic sensors

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A R T I C L E I N F O

Article history:
Received 9 June 2015
Received in revised form
23 September 2015
Accepted 25 September 2015
Available online 28 September 2015

Keywords:
Mechanism detection
SAW gas sensors
Selective thin film properties
Density
Young's modulus
Phase velocity
FEM
Hydrogen

A B S T R A C T

This paper explains the sensing mechanism of acoustic hydrogen gas sensors based on Surface Acoustic Waves (SAWs). The main idea is to take advantage of the presence of two different modes of vibration to extract independently density and stiffness of the studied thin film. The adopted methodology is based on a parametric study determining the variation in the phase velocity of the sensitive layer according to thin film parameters. Then, the experimental extraction of this phase velocity allows the determination of the thin film experimental parameter values by using the established model. This new methodology allows the measuring of the density and Young's modulus of thin films in hydrogen atmosphere. Also, it improves the study of sensing mechanism in the thin films. Especially, since the analysis of the sensitive layer's properties within a gaseous atmosphere is not simple.

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1. Introduction

In order to minimize the impact of greenhouse gas emissions, manufacturers have turned to the use of new technologies based on clean and renewable energy such as hydrogen [1]. However, exploiting these new energies requires the use of detection devices, especially to detect any gas leaks and improve safety for the final user [2]. A first generation of hydrogen gas sensors

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http://dx.doi.org/10.1016/j.snb.2015.09.130
0925-4005/

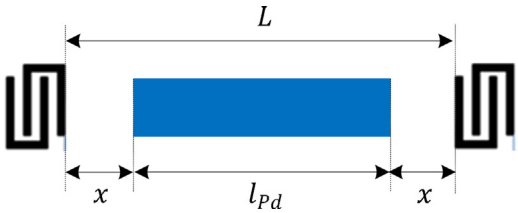

Fig. 1. Sensor delay line with palladium film.

based on catalytic, electrochemical, thermal conductivity, metal oxide, and MOS technologies has already been commercialized and used in the automotive industry. However, they do not meet the requirements of the automotive industry, especially in terms of robustness, performance, reliability and safety [3–7].

To mitigate these problems, new emerging technologies based on Micro/Nano Electromechanical Systems have been proposed [8–12], which exploit their robustness and high quality factors [3]. However, these types of technologies are complex to realize. Another much exploited technology is Acoustic technology. These devices present a good reliability and robustness in harsh environments, combined with low manufacturing costs [13–24]. However, some sensors based on this type of technology still have some operation weaknesses [3]. Thus, to overcome these weaknesses, understanding their sensing mechanism is required. This will allow required optimizations.

As with most gas sensors, the detection principle is based on the use of sensitive layers able to absorb hydrogen molecules. Thus, many studies have been conducted to understand the sensing mechanisms of gas sensors. Three main parameters are often involved in the sensing mechanism of acoustic sensors: electrical effect (conductivity) [25–27], mass effect (density), and mechanical effect (Young's modulus) [28–31]. Some of the conducted studies have demonstrated that, under some conditions with respect to the conductivity and thickness of the sensitive films, only variations in density and Young's modulus impact the propagation of acoustic waves. However, these studies do not detail the relative contribution of each of them. It would be beneficial to distinguish the relative contribution of the two parameters in order to determine which parameter influences the sensing mechanism the most. This would promote one parameter over the other, depending on the intended application. Additionally, the analysis of the sensitive layer's properties within a gaseous atmosphere is not simple. Actually, there is no way to determine the variation of these parameters in a gaseous atmosphere. This paper presents a methodology allowing the extraction of different properties of said sensitive layer absorbing hydrogen in the atmosphere. Thus, the new methodology presented in this paper explains the sensing mechanism in acoustic hydrogen gas sensors. This study will determine the effects and the proportion of each parameter of the sensing mechanism of acoustic hydrogen gas sensors. This will also allow the optimization of future generations of new acoustic gas sensors.

The first section presents a theoretical study and the adopted approach based on a Finite Element Model. In the following section, the tests of experimental sensors in the presence and absence of hydrogen will thus be presented. Then, the extraction of practical values of the studied parameters will be done, determining the effective contribution of each parameter and thus explaining the sensing mechanism of acoustic hydrogen gas sensors.

2. Theory

The methodology used to explain the sensing mechanism is presented in this section. The base structure for the acoustic sensors is the SAW delay-line sketched in Fig. 1: a patch of sensitive Pd film is deposited between two interdigitated transducers. Depending on the crystallographic orientation of the lithium niobate wafer on which this structure is fabricated, different modes may be exploited.

2.1. Proposed approach

The adopted approach is as follows: first, the identification of two different exploited acoustic modes is required. Indeed, some orientations of lithium niobate support two piezoelectrically active surface modes – a Quasi-SAW mode with quasi-elliptical polarization and a Shear-Horizontal (SH) mode with transverse polarization. The two modes exhibit a slightly different propagation velocity, resulting in two separate contributions visible on the electrical response of the delay line.

The number of exploited modes must be equal to the number of studied parameters. In the present case, two parameters are studied. Second, the studied parameters are identified, and their variation ranges and the step between each two consecutive points are established. Then, based on the finite element model, a parametric study for each studied mode is done. This establishes a relationship between the variation of the phase velocity and the variation of density and Young's modulus of the thin film. Eventually, the effective phase velocity for the different modes studied is extracted from electrical measurements using the following formula:

$$V_{\mathrm{Pd}} = \frac{l_{\mathrm{Pd}} v}{l_{\mathrm{Pd}} + \frac{v \Delta\varphi}{360 f}} \qquad (1)$$

It includes V_{Pd}, the experimental acoustic wave phase velocity in the palladium region (identified with "l_{Pd}" in Fig. 1), v, the acoustic wave phase velocity in the lithium niobate region (identified with "x" in Fig. 1), f, the operating frequency, $\Delta\varphi$, the phase shift (in degrees) between the two delay lines of the sensor, the line with palladium film and the line without the palladium film, and l_{Pd}, the sensitive thin film length.

Assuming that the two wave velocities in the Pd-coated section of the delay line are related to both Young's modulus and density of the film, these two measurements provide a set of two equations based on two unknowns. Hence, the effective mechanical parameters of the film can be obtained by a simple system inversion. Fig. 2 summarizes the adopted approach. The figure demonstrates the methodology adopted and which allows the extraction of the studied parameter values in gaseous environment. First, it is necessary to identify the two exploited acoustic modes and the studied thin layer parameters. In our case, Quasi-SAW and SH-SAW modes are exploited in order to determine the hydrogen effect on the Young's modulus and the density of the sensitive layer. Then, it is necessary to establish the variation of phase velocity as function of studied parameters, density and Young's modulus. The relationship is established for the two studied modes using a parametric model. Finally, the experimental extraction of this phase velocity allows establishing two equations with two unknowns. Solving this system of equations allows the determination of the experimental values of studied parameters. Thus, it allows the determination of the hydrogen effect on thin film studied parameters.

2.2. Finite element model building

In this subsection, we start by describing how we establish the theoretical dependence of the phase velocity in the Pd-covered region of the sensor on the studied parameters. Then, we provide examples for the two acoustic modes identified in this study.