Sensitivity Comparison between Surface Acoustic Wave and Lamb Acoustic Wave Hydrogen Gas Sensors

Assane Ndieguene, Issam Kerroum, Frédéric Domingue
Laboratoire des Microsystèmes et Télécommunications
Université du Québec à Trois-Rivières
Trois-Rivières, Canada
emails: {Assane.Ndieguene, Issam.Kerroum, Frederic.Domingue}@uqtr.ca;

Alexandre Reinhardt
Laboratoire d'Électronique et des Technologies de l'Information,
CEA, LETI
Grenoble, France
email:alexandre.reinhardt@cea.fr;

Abstract— **This paper presents a sensitivity study of acoustic hydrogen gas sensors. The study emphasises on the comparison between sensitivity of Surface Acoustic Wave (SAW) hydrogen gas and new acoustic hydrogen sensors based on Lamb waves. To highlight this comparison, a parametric model based on the variation of mechanical and physical properties of Palladium sensitive layers has been implemented. This results show that SAW wave devices are more sensitive to Young's modulus variations than Lamb Acoustic Wave devices.**

Keywords-acoustic hydrogen sensor; Lamb and surface acoustic waves; FEM; sensitivity.

I. INTRODUCTION

Due to the increasing demand on hydrogen gas sensors for several applications such as automation, transportation, or environmental monitoring, the need for sensitive and reliable sensors with a short response time is increasing [1-2]. The purpose of gas sensors is to analysis residual gas in a reservoir, to insure an optimal security in hydrogen vehicles, or to satisfy the current gas detection requirements. Therefore, in the recent years, the trend has been towards exploiting new emerging sensing technologies. One of most used technologies is the acoustic technology. Most of the developed acoustic sensors are based on Surface Acoustic Waves (SAW) [3-5]. These devices present a good reliability and robustness in harsh environments, combined with low fabrication cost. In addition, SAW devices are passive, that reduces power consumption [6-8]. Recently, some work has been devoted to Lamb wave resonators [9], which is said to exhibit promising performances for biological detection due to their improved mass sensitivity.

In this paper, a sensitivity comparison between SAW and Lamb wave devices is presented, in order to compare their suitability to hydrogen gas sensing.

Because of its high ability to interact with hydrogen molecules, Palladium (Pd) is often used as a sensitive layer to detect the presence of hydrogen gas [10-12] in SAW delay lines. In this work, 3% hydrogen concentration is considered and in this case, the Palladium density and Young's modulus decrease by 2% and 14% respectively with an $\pm 20\%$ error [13-14]. Based on finite element simulations, a parametric study technique has been used to analyze the impact of physical and mechanical parameters variations of a sensitive layer on the frequency of SAW and Lamb wave delay lines.

The different between acoustic modes used to perform the sensitivity analysis is presented in Section 2. In Section 3, the methodology and the finite element models are presented together with a comparison between frequency bands. Section 4 is devoted to the presentation of the obtained results and the analysis. The conclusion will be used to summarize main obtained results and analysis.

II. METHODOLOGY

A. Selected Modes Characteristics

This sensitivity comparison is based on analysing three different modes with different characteristics: two Lamb wave modes using Aluminum Nitride (AlN) membrane - the symmetric S_0 Lamb mode operating at low frequencies and an anti-symmetric A_1 Lamb mode operating at high frequencies above its cut-off frequency – and the Rayleigh mode propagating on the Lithium Niobate ($LiNbO_3$) substrate. The shape of these modes obtained by Comsol is shown in Fig. 1.

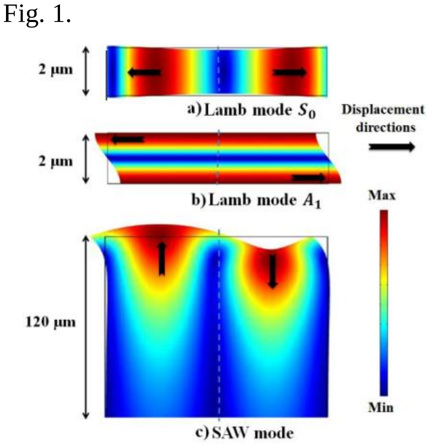

Figure 1. Comparison of the considered vibration modes: (a) S_0 Lamb mode , (b) A_1 Lamb mode and (c) Rayleigh mode substrate deformation

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The S_0 Lamb mode corresponds to a compression or an extension of the piezoelectric plate along the propagation direction. Its deformations are homogeneous in the thickness of the plate. The A_1 mode corresponds to shearing in the thickness-direction of the membrane. For a $LiNbO_3$ substrate, the Rayleigh mode corresponds to an elliptic displacement in the sagittal plane and is evanescent in the thickness of the medium.

B. *Sensitivity Comparison Method*

To perform this comparison, the methodology used is based on a parametric study using Comsol. A model based on small simultaneous variations of sensitive layer properties (Young's modulus and density) is implemented. Initial values for Palladium Young's modulus and density are equal to $E_0 = 174\ GPa$ and $\rho_0 = 12020\ kg/m^3$ respectively. To cover most of the cases, a variation of $\pm 5\%$ for ρ_0 with a step of 0.8% and $\pm 20\%$ for E_0 with a step of 3.1% will be considered in the parametric study. Then, a reduced equation that shows the dependence of the operating frequency to the variations of the studied parameters is established by curve fitting method. This equation will highlight the sensitivity comparison between studied acoustic modes. The following diagram shown in Fig. 2 summarizes the path adopted to establish this equation.

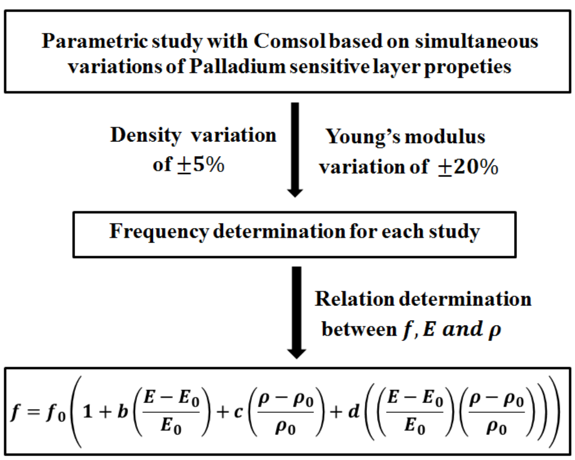

Figure 2. Flow chart summarizing the steps of calculating the relation between the frequency, the density and the Young modulus.

where b is the constant related to the sensitivity of Young's modulus, c is the constant related to the sensitivity of the density and d the interrelationship constant. To determine the equation used as model to perform the sensitivity, another high-order equations (second and fourth order) is explored. This study revealed that the fit and the residuals obtained from high-order equations are better than the established equation in Fig. 2. However, the use of high-order equations is more complex. Thus, for the sensitivity study the equation of first order will be adopted.

C. *Finite Element Model Building*

A c-axis oriented AlN plate is used for Lamb modes and a Y/Z $LiNbO_3$ cut for SAW mode. The description of the geometries used to perform sensitivity studies is represented in Fig. 3.

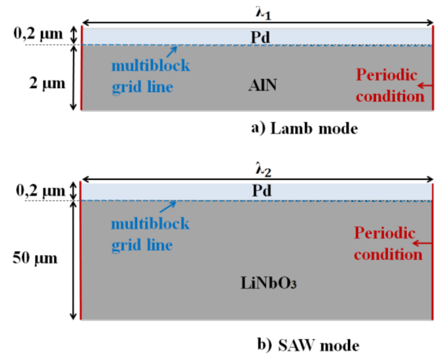

Figure 3. Comsol model proposed for the study of sensitivity: a) Lamb mode and b) SAW mode.

For each studied mode, piezoelectric, linear elastic and electrical models are used. To ensure continuity between blocks, multiblock and conformal mesh are used. Finally, Floquet periodic boundary conditions at the edges of the model are imposed to force a wavelength in the propagation direction.

D. *Frequency Band Identification*

Sensitivity studies are conducted around the ISM frequency bands: 433 MHz – 435 MHz and 902 MHz – 928 MHz. To design the geometry of the excitation electrodes (period of interdigitated electrodes), the dispersion curves of the first four Lamb wave modes in a 2 µm c-axis oriented AlN plate is plotted, as shown in Fig. 4.

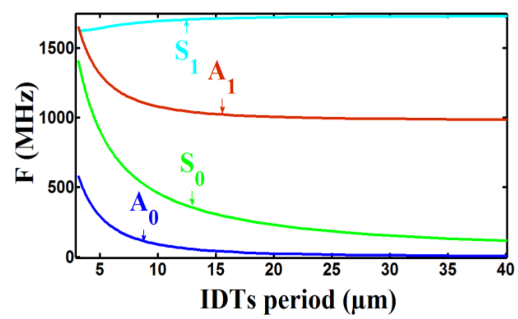

Figure 4. Dispersion curves for a 2 µm c-axis oriented AlN plate.

From these dispersion curves, the S_0 mode operates in the 430 MHz ISM band for electrode period of around 10 µm. The A_1 mode operates in the 920 MHz ISM band for electrode periods around 20 µm. These results are summarized in Table I.

TABLE I. ISM BAND IDENTIFICATION AND FINGERS PERIOD

Modes Selected	*ISM Band (MHz)*	*Fingers period (µm)*	*Wavelength (µm)*
S0	*433.05 – 434.79*	*10*	*20*
A1	*902 – 928*	*20*	*40*
SAW	*433.05 – 434.79 or 902 - 928*	*4 or 1.5*	*8 or 3*

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The comparison between SAW and Lamb modes has been done in the same ISM bands frequency.

III. RESULTS AND DISCUSSIONS

A. S_0 Lamb and Rayleigh Mode Sensitivity Comparison

From parametric study proposed in Fig. 2, a relation between frequency and the Palladium various parameters is established, see equation 1.

$$f = f_0\left(1 + b\left(\frac{E-E_0}{E_0}\right) + c\left(\frac{\rho-\rho_0}{\rho_0}\right) + d\left(\frac{E-E_0}{E_0}\right)\left(\frac{\rho-\rho_0}{\rho_0}\right)\right) \quad (1)$$

This equation is used for Rayleigh and S_0 Lamb mode in order to determine the sensitivity of the frequency to the various parameters. The different constants for theses equations are shown in Table II.

TABLE II. S_0 LAMB AND RAYLEIGH MODE SENSITIVITY COMPARISON

Mode sensitivity	*b*	*c*	*d*
S_0	0.0321	-0.1529	0.0027
Rayleigh	0.0421	-0.1070	0.0071

These results show that the Rayleigh mode is more sensitive to changes in Pd stiffness than the S_0 Lamb mode. However, the S_0 Lamb mode is more sensitive to the mass loading effect than the Rayleigh mode. The initial frequency for Rayleigh mode and S_0 Lamb mode are 442 MHz and 476 MHz respectively. In the presence of 3% hydrogen concentration, density decreases by 5% and Young modulus by 20%. The expected frequencies are 440 MHz for the Rayleigh mode and 476 MHz for the S_0 Lamb mode. This shows that the Rayleigh mode is slightly more sensitive (0.45% frequency shift) than the S_0 Lamb mode for which the effect of Pd film stiffening and the mass-loading compensate each other.

B. A_1 Lamb and Rayleigh Mode Sensitivity Comparison

The same analysis was performed to compare the sensitivity between A_1 Lamb mode and Rayleigh mode in the same frequency band.

For each mode, material constants related to the sensitivity properties of the Pd layer are extracted from the set of parametric simulations.

TABLE III. A_1 LAMB MODE AND RAYLEIGH MODE SENSITIVITY COMPARISON

Mode sensitivity	*b*	*c*	*d*
A_1	0.0293	-0.1941	0.0195
Rayleigh	0.0774	-0.2130	0.0078

In this case, the Rayleigh mode is more sensitive to all changes in material properties of the Pd film. In addition, the initial value and the expected value of the frequency are 1082 MHz and 1075 MHz respectively for Rayleigh mode, resulting in a 0.65 % frequency shift. For the A_1 Lamb mode, the initial value is 1154 MHz and the expected value is 1155 MHz, that leads to a 0.09% frequency shift. It is also interesting to note that with the increase in operation frequency, the Rayleigh mode has become more sensitive to added mass and increased stiffness. This is attributed to the decreasing of penetration depth at higher frequency, and therefore a better confinement of vibrations at the vicinity of the sensitive material.

IV. CONCLUSION AND FUTURE WORK

In this paper, the sensitivity comparison between the classical SAW hydrogen gas sensor and future potential hydrogen gas sensors based on Lamb waves was presented. This comparison was performed considering delay lines operating in the ISM bands, at around 430 MHz and 920 MHz. Theoretical evaluations showed that, in the presence of 3 % hydrogen concentration, gas acoustic sensors based on Rayleigh waves are more sensitive to hydrogen than similar Lamb wave sensors. To generalize these results, other comparative studies will be conducted to determine the influence of hydrogen concentration.

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