Proceedings of the 2nd EAA International
Symposium on Hydroacoustics
24-27 May 1999, Gdańsk-Jurata
POLAND

Modelling of SAW liquid sensors

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Surface Acoustic Wave (SAW) devices are used in variety of sensing application. This paper describes the sensors operated with shear horizontal (SH) mode wave, in liquid. Liquid sensors of conductivity and viscosity are described and results of modelling of their properties are given. Parameters of SH mode sensors design are also given.

1. Introduction

Surface acoustic wave (SAW) could be used as sensing elements for the evaluation of liquid phased material. Conventional Rayleigh's SAW devices and Lamb wave devices have been applied successfully as gas sensor. Liquid phased materials introduce strong attenuation of surface wave modes which include vertical displacement component, hence shear horizontal (SH) wave modes are more useful.

The particle displacement in the SH mode is parallel to the device surface and normal to the direction of propagation. Figure 1 shows propagation of SH wave mode. IDT is an interdigital transducer, which excites an acoustic wave in the piezoelectric substrate.

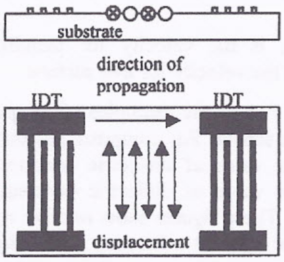

Fig.1. Propagation of SH mode wave.

There are several types of SH modes: SH-SAW [1][2][4][5][6], SH-APM (Acoustic Plate Mode)[7][8] and Love-wave [9][10]. Figure 2 shows an APM device. It consists of a thin plate, where acoustic wave propagates through multiple reflection. Love-wave propagates in a layered structure consisting of substrate and an overlayer very thin dielectric film, which guides wave towards subsurface region.

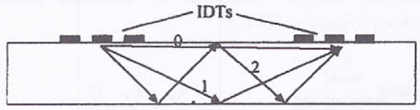

Fig. 2. Propagation of APM mode.

SH mode devices could be used for the measurement of liquid properties such as: conductivity, permittivity and viscosity.

For example, in work [5] liquid viscosity of solutions: water/glycerol and water/sucrose was measured. Sensor based on substrate 41YX $LiNbO_3$ (41° rotated Y-cut, X-propagation) was used. Sensor has a sensitivity of about 80Hz/cP at an operating frequency of 30MHz and threshold sensitivity of about 1cP.

In work [6] SH wave device was applied for identification system for ionic solution. Unknown ionic solution was identified using databases. Databases created on the basis of measurements such aqueous solutions as: HCl, KCl, $MgCl_2$, $AlCl_3$, $CaCl_3$, BaC_{12}. Sensor based on substrate 36YX$LiTaO_3$, the sensor can detect electrical properties of liquid with high sensitivity because $LiTaO_3$ have a large electromechanical coupling coefficient.

In work [4] KCl conductivity of the solution was measured by using sensor with SH wave. Frequency of the oscillator varied more than 80kHz for variation in KCl concentration from 0 to 0.15%. Sensor based on substrate ZX $LiNbO_3$.

In work [7] APM device based on substrate ZX LiNbO3 was used. Several dilute aqueous solutions such as: $Mg(NO_3)_2$, $Fe(NO_3)_3$, $Cu(NO_3)_2$, $CaCl_2$ were tested (up to 0.35 weight percent). Concentration of dilute electrolytes or metal ion solutions was extracted from the measured a conductivity. The results indicate detectability in order of 1ppm of the concentration.

2. Measurement method

To excite proper waves mode it is necessary to choose proper kind of substrate, crystal cutting, direction of propagation of acoustic wave and proper location of the interdigital transducers.

Figure 3 shows interdigital transducer IDT. On the figure W is the aperture and L is the periodicity of the transducer. Acoustic wavelength is equal periodicity for the optimal value of frequency. Figure 3 shows equivalent electrical scheme of IDT. Elements values of the model depend on geometrical dimensions of IDT and parameters of the substrate such as: an electromechanical coupling coefficient and permittivity [3]. Knowledge of values of these elements unable selection of external electrical devices joined to IDT's.

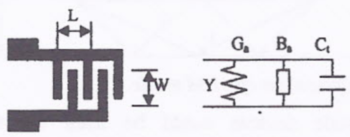

Fig. 3. Transducer IDT and his equivalent electrical scheme.

Sensor consists of piezoelectric substrate and two IDTs in the simplest case. That system creates delay line. The first transducer converts the electric energy into the SAW energy, whereas the second transducer inversely. Change of solution density, viscosity and conductivity influences the propagation of wave between IDTs when solution contacts the surface of sensor.

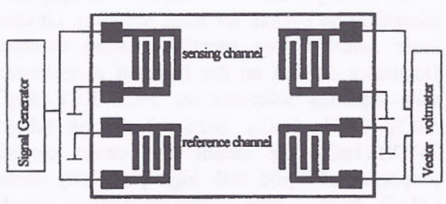

Fig.4 Sensor with two delay lines

Figure 4 shows sensor with two channels (two delay lines): sensing and reference. Channels are driven by an external oscillator. Phase difference and amplitude ratio between reference and sensing channel are monitors by a vector voltmeter. System provides compensation of temperature influence. The SH-SAW that propagates on a free surface is affected by both the electrical and mechanical properties of the liquid. Application of metallized surface in one channel causes elimination of influence of liquid conductivity. The SH-SAW that propagates on metallized surface is affected only by the mechanical properties of the liquid such as viscosity. By detecting the differential output signal between metallized and free surface the only electrical properties are measured.

3. Sensor for conductive liquids

Changes of solution conductivity influence directly electrical field coupled with acoustic wave. Wave velocity and normalised attenuation γ change according to [8]:

$$\frac{\Delta V}{V} = \left(-\frac{1}{2}\right) K^2 \frac{\varepsilon_S}{\varepsilon_S + \varepsilon_L} \frac{\sigma^2}{\sigma^2 + \omega^2 (\varepsilon_S + \varepsilon_L)^2}$$

$$\gamma = \left(-\frac{1}{2}\right) K^2 \frac{\varepsilon_S}{\varepsilon_S + \varepsilon_L} \frac{\omega\sigma(\varepsilon_S + \varepsilon_L)}{\sigma^2 + \omega^2 (\varepsilon_S + \varepsilon_L)^2}$$

, where: K^2 - is the electromechanical coupling coefficient, ε_S - permittivity of the substrate, ε_L - permittivity of the liquid, σ - conductivity of the liquid, ω - the angular frequency.

The electromechanical coupling coefficient depends on the substrate. For the SAW the electromechanical coupling coefficient can be related to fractional difference between the free and metallized surface wave velocity:

$$\left(\frac{1}{2}\right) K^2 = \frac{V_f - V_m}{V_f}$$

, where: V_m is the velocity for metallized surface and V_f is the velocity for free surface.

Figures 5, 6, 7 show the examples of computer modelling of the sensor. For computer simulation we assumed that value of dielectric constant of solution is equal value of dielectric constant of deionized water. These figures show relative wave velocity change as a function of liquid conductivity for varying parameters such as: operating frequency - f, electromechanical coupling coefficient - K^2 and the substrate permittivity - ε_S. It can be seen that the relative wave velocity change increase with increasing the liquid conductivity, but velocity change saturates. Figure 5 shows velocity change at change of value of frequency. At lower frequency is obtained stronger increase and saturation for the smaller liquid conductivity. Saturation of velocity change for frequency f1=50MHz is obtain for value of liquid conductivity near 2[S/m]. For this case we assumed the value of parameters: K^2=0.15 and ε_S=48ε_0.

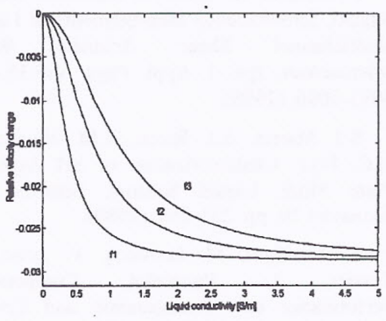

Fig.5. Relative velocity change versus liquid conductivity for three different values of frequencies: f1=50MHz, f2=100MHz and f3=150MHz.

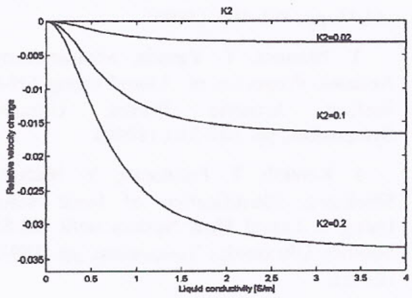

Fig.6. Relative velocity change versus liquid conductivity for three different values of electromechanical coupling coefficients: K^2=0.02, 0.1 and 0.2.

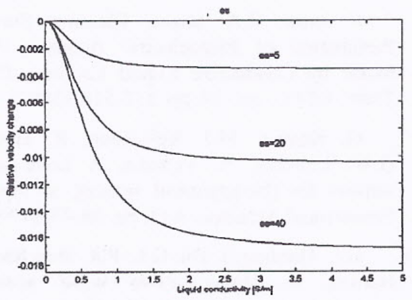

Fig.7. Relative velocity change vs. liquid conductivity for three different values of substrate permittivity ε_S: 5ε_0, 20ε_0 and 40ε_0.

Figure 6 shows velocity change versus change of electromechanical coupling coefficient. For the higher values of electromechanical coupling coefficient is the larger velocity change and higher saturation level is shown. For this case we assumed the value of parameters: f=100MHz and ε_S=40ε_0. Figure 7 shows how the velocity changes at change of substrate permittivity. For a higher value of substrate permittivity the larger velocity change and higher saturation level are. For this case we assumed the value of parameters: f=100MHz and K^2=0.15.

4. Sensor of liquid viscosity.

Relative change velocity $\Delta V/V$ and attenuation γ due to contact with liquid is given by [1]:

$$\frac{\Delta V}{V} = -\frac{V\upsilon^2}{4\omega P}\mathrm{Im}(Z);\ \gamma = \frac{V\upsilon^2}{4\omega P}\mathrm{Re}(Z)\cdot$$

, where: V is the phase velocity, ω is an angular frequency, υ is the particle velocity component of SH mode, P is the power flow per unit width. Term $V\upsilon^2/4\omega P$ is a device sensitivity, which depends on parameters of the substrate. Term Z is the surface impedance for adjacent viscosity liquid. It is defined as: $Z = -\left(\sqrt{j\omega\eta\rho}\right)$, assuming viscous Newtonian liquid model with viscosity η and density ρ.

For example, we assumed lithium niobate substrate, value of density liquid 1000kg/m3, and liquid viscosity change in range from 0 to 0,5[Pa*s/m^2]. Figure (8) shows dependence between relative wave velocity change and an expression $\sqrt{\eta\rho}$ for two frequencies (f1=50MHz and f2=150MHz). Wave velocity change is proportional to $\sqrt{\eta\rho}$. For a higher liquid viscosity and/or higher frequency the larger velocity change are.

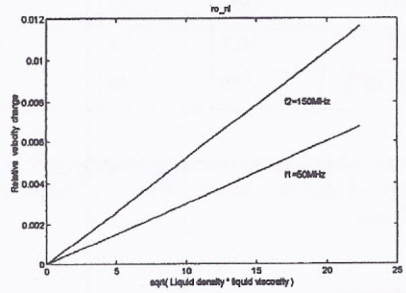

Fig.8. Relative velocity change vs. product liquid viscosity and density for two values of frequency: f1=50MHz and f2=150MHz.

Newtonian model is effective for low frequencies and low viscosity. For higher frequencies $\omega\tau$>>1 liquid behaves as a solid with shear stiffness μ_∞, where $\tau=\eta/\mu_\infty$ is a characteristic relaxation time Then the viscous liquid can be considered as a Maxwellian liquid model.

5. Sensor design

Structures of sensors with SH wave mode were designed and made. There are three groups of sensor. Each of groups has different material of substrate. Materials such as: lithium niobate, lithium tantalate and langasit were selected for sensors. There are substrates: 37°Y-cut X-prop. $LiNbO_3$, 35°Y-cut X-prop. $LiTaO_3$ and 53° X-prop LGS ($La_3Ga_5SiO_{14}$). Figure 9 shows a single structure. The substrate has a dimensions 35mm x 8mm. There are four IDTs on the single substrate, which create two channels.

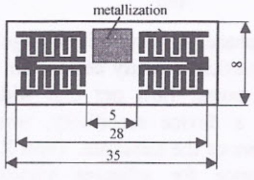

Fig.9. The SH mode sensors design.

Figure 9 shows location the IDTs. Metallization was made in one of the channels. Table I includes the other parameters.

Table I. Parameters of designed sensors.

Substrate	$LiNbO_3$	$LiTaO_3$	LGS $La_3Ga_5SiO_{14}$
Cutting and Propagation	37°Y-cut, X-prop	35°Y-cut, X-prop.	53° X-prop
f_0 [MHz]	91,2	80,2	49,4
Δf [MHz]	2,6	2,3	1,4
V [m/s]	4802	4221	2600
K^2 [%]	16,7	4,7	0,38
TCD[$x10^{-6}$]	59	45	50

In the table f_0 is the operating frequency, V is the velocity of acoustic wave, TCD is a temperature coefficient.

Conclusions

Computer modelling of the SH type liquid sensors shows the real theoretical possibilities of measuring of the liquid phased materials properties with using of such type sensors. The sensor series was designed and their practical properties will be presented during the Symposium.

Acknowledgements

This work was supported by Polish Committee of Scientific Research grant No. 8 T11 B 023 15.

Reference

1. J. Kondoh, K. Saito, S. Shiokawa and H. Suzuki, Simultaneous Measurements of Liquid Multichannel Shear Acoustic Wave Microsensor, Jpn. J. Appl. Phys. Vol.35, pp. 3093-3096, (1996).
2. S.J. Martin, A.J. Ricco, T.M. Niemczyk, G.C. Frye, Characterization of SH Acoustic Plate Mode Liquid Sensors, Sensors and Actuators 20, pp. 253-268, (1989).
3. G. Feuillard, M. Lethiecq, Y. Janin, L. Tessier, L. Pourcelot, Comparative Performance of Piezoceramic and Crystal SAW Filters, IEEE Trans. UFFC, vol. 44, pp. 194-198, (1997).
4. Y. Jin, S.G. Joshi, Propagation of a Quasi-Shear Horizontal Acoustic Wave in Z-X Lithum Niobate Plates, IEEE Trans. UFFC, vol.43, pp. 491-494, (1996).
5. T. Nomura, T. Yasuda, Measurement of Acoustic Properties of Liquid Using SH-type Surface Acoustic Waves, Ultrasonics Symposium, pp. 307-310, (1990).
6. J. Kondoh, T. Furukawa, Y. Matsui, S. Shiokawa, Identification of Ionic Solution Using A Liquid Flow System with SH-SAW Sensors, Ultrasonics Symposium, pp. 389-394, (1996).
7. S. Liew, F. Josse, D.T. Haworth, Z.A. Shana, U.R. Kelkar, M.Grunze, Applications of Lithium Niobate Acoustic Plate Mode as Sensor for Conductive Liquids, Ultrasonics Symposium, pp. 285-290, (1990).
8. F. Josse, Z.A. Shana, Elecrical Surface Pertubation of Piezoelectric Acoustic Plate Mode by Conductive Liquid Loading, IEEE Trans. UFFC, vol. 39, pp. 512-518, (1992).
9. G. Kovacs, M.J. Vellekoop, R. Haueis, G.W. Lubking, A. Venema, A Love wave sensors for (bio)chemical sensing in liquids, Sensors and Actuators A43, pp. 38-43, (1994).
10. G.L. Harding, J. Du, G.L, P.R. Dencher, D. Barnett, E. Howe, Love wave acoustic immunosensor operating in liquid, Sensors and Actuators A61, pp. 279-286, (1997).