

Acoustic Love plate sensors: a theoretical model for the optimization of the surface mass sensitivity

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1. Introduction

In general, the surface mass sensitivity of an acoustic chemical sensor is inferior to that of an acoustic gas sensor [1, 2]. This arises because the energy of the acoustic wave mode is focused at the air/solid interface of the gas-phase sensor, but defocused at the interface of the liquid-phase sensor. To focus energy at the liquid/solid interface, an oriented single-crystal baselayer and a surface coating of an overlayer can be utilized. This configuration, which supports acoustic Love waves, can be constructed by modifying a standard surface-skimming bulk wave (SSBW) device with a deposited overlayer of, for example, silica or gold. In operation, small interfacial mass changes in the liquid phase will change the velocity of the Love wave [3]. If the acoustic wave is more focused at the interface, the velocity change and therefore the sensitivity will increase. As the material characteristics of the Love wave device are likely to affect the device sensitivity, a theoretical analysis was undertaken to indicate the most useful materials.

2. A model for predicting the performance of a Love-wave device

The surface mass sensitivity of a Love guide is an important factor in its successful implementation as an acoustic chemical sensor. The basis for calculating this mass sensitivity is an expression derived by Auld [4]:

$$\frac{\Delta\beta/\beta}{[h\rho]} = \frac{1}{4} \frac{\omega [v_y]^2}{\beta P} \quad (1)$$

where $(\Delta\beta/\beta)/[h\rho]$ is a figure of merit for the guide's mass sensitivity, β is the propagation constant, $h\rho$ is the surface mass density, ω is the angular frequency of operation, v_y is the in-surface SH (shear horizontal) component of the velocity of particle motion and P is the time-average power flow per unit width. The critical terms are v_y , which is proportional to the shear surface displacement, and P , which depends on the shear amplitude as a function of depth. Of importance is

arranging for a significant v_y/P ratio, as this implies a large surface displacement and a shear amplitude that decays rapidly with depth. This is equivalent to an acoustic wave focused at the liquid/solid interface. Varying the mechanical conditions, i.e., choosing overlayers with different densities and shear velocities, affects the v_y/P ratio and suggests a possible approach for optimizing the mass sensitivity. This is demonstrated by plotting the computational solutions for v_y and P in eqn. (1) as a function of the density and shear velocity of the overlayer (Fig. 1).

Figure 1 specifies the change in the operating frequency in Hz for an optimally thick overlayer in response to a unitary surface-density change of 1 ng/cm^2 . The maximum attainable sensitivities for devices coated with a selection of overlayer materials are indicated by the contours. For other overlayer materials, information on the shear acoustic velocity and density is required. This allows an experimentalist to determine an approximate value for the mass sensitivity of a Love-wave device. To simplify the interpretation of these results, all the indicated values are normalized for a standard device operating at 110 MHz with the specified overlayer and a 0.5 mm thick ST quartz baselayer (acoustic shear velocity 4952 m s^{-1} , density 2200 kg/m^3).

If a suitable material has been selected for the overlayer, it is still necessary to define the thickness.

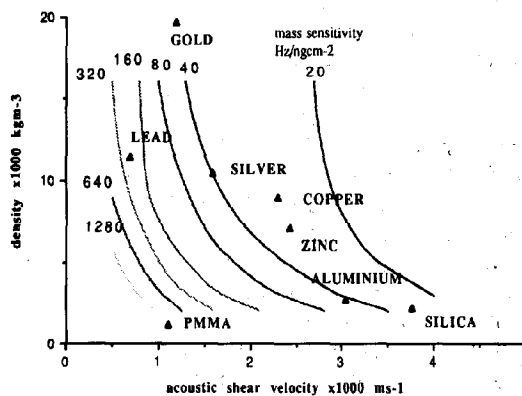


Fig. 1. Relation between the mass sensitivity and the overlayer material.

TABLE 1. The thickness and properties of various overlayer materials corresponding to optimum sensitivity

Material	Shear acoustic velocity (m s^{-1})	Density (kg m^{-3})	Sensitivity (Hz/ng cm^{-2})	Thickness (μm)
Fused silica	3764	2200	15	12
Aluminium	2700	3040	50	9
Copper	2325	8930	15	7
Zinc	2440	7100	16	7
Silver	1610	10400	20	1-2
Gold	1200	19700	20	1-2
Lead	700	11400	120	1-2
PMMA	1100	1180	1500	3

This is because increasing the thickness of the overlayer from zero results in the mass sensitivity rising almost linearly to a peak and then decreasing asymptotically to a constant value. The position of this mass-sensitivity peak can be determined approximately from the following simplified summary of the calculated data: for the values of density and velocity considered in Fig. 1, the optimum overlayer thicknesses are found between 1 and 12 μm . Thinner coating thicknesses of 1-2 μm apply to the high-density materials ($> 10\,000\text{ kg m}^{-3}$), whereas 3-12 μm thicknesses apply to the low-density materials ($< 10\,000\text{ kg m}^{-3}$). If the overlayer shear acoustic velocity is also considered, it is possible to select the thickness of the low-density materials more accurately. For example, at 4000 m s^{-1} the overlayer thickness is optimum at around 12 μm and for 1000 m s^{-1} , the optimum is closer to 3 μm . Example overlayer materials are listed in Table 1.

3. Discussion

The results of the calculation of the mass sensitivity of a Love guide have suggested that the most reliable indicator of its magnitude is the shear acoustic velocity of the overlayer material. Density is less important. Overall, significant mass sensitivities are anticipated for overlayer materials with minimal shear velocities, which direct the acoustic energy more proximally to the sensing surface. In addition, the form of the mass sensitivity versus thickness function differs with the type of overlayer material. Metallic materials exhibit a mass sensitivity that is broadly distributed with thickness; however, polymer materials exhibit a disadvantageous sharp peak. This suggests that the optimum thickness of the polymer overlayer may practically be difficult to define, resulting in the lower sensitivity predicted at thicknesses either side of the peak.

In general, a possible deficiency of the model, which may ultimately explain any discrepancies, is the exclusion of the acoustic transmission losses. For this reason caution should be exercised in applying the model to

polycrystalline materials, as they exhibit absorption increasing proportionally to f^4 at a wavelength comparable to the grain size. This makes them very lossy beyond a few MHz. For use at higher frequencies, single crystals or amorphous materials are preferable guide materials as they avoid the losses associated with the presence of grains. Typically, single crystals such as the regularly used piezo-quartz materials for the baselayer still remain relatively lossless up to a few GHz, whereas amorphous materials have more significant frequency limitations. For example, glass and fused silica allow significant propagation at frequencies up to $\approx 150\text{ MHz}$.

Suitable overlayers can also be made from polymeric materials such as polyethylene, polymethylmethacrylate (PMMA) and polyethylene oxide, even though considerable quantities of energy can be lost by relaxation processes. For example, PMMA has extraordinary relaxation losses of 200 dB/cm at 100 MHz, but is still usable as a coating for sensitive Love devices. This can be explained by acoustic transmission in the baselayer supporting the propagating mode. However, if a significant fraction of the acoustic signal is directed through the lossy overlayer, which may occur at high surface sensitivities, catastrophic signal losses can arise. Finally, a discrepancy may also arise because of the assumption that viscous losses in the aqueous environment are negligible for shear horizontal waves, which may not be the case for highly sensitive guide arrangements.

4. Conclusions

The model suggests that an effective Love device is more dependent on the difference between the shear velocity than the density of the substrate or overlayer. It also predicts the mass sensitivity for a wide range of overlayer materials, allowing more opportunity for the experimenter to select the chemically appropriate surfaces for liquid- and gas-phase mass sensing. In addition the predicted mass sensitivity assists in defining the performance requirements for the supporting sensor electronics and in determining whether the detection

of the likely concentration of the test species is feasible. Finally, polymer overlayers have been found to offer significant gains in mass sensitivity; however, their other demerits, such as acoustic loss and instability, should be accounted for.

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