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A Novel Love-Plate Acoustic Sensor Utilizing Polymer Overlayers

Electra Gizeli, Adrian C. Stevenson, Nicholas J. Goddard, and Christopher R. Lowe

Abstract—**A Love-plate sensor, consisting of a SSBW device coated with a polymer layer, was found to increase the acoustic signal through coupling of the SSBW wave to a Love wave. Insertion loss, phase and frequency measurements were used to assess the optimum thickness of the polymer layer and the sensitivity of the device to mass-loading and viscous coupling.**

I. INTRODUCTION

Surface skimming bulk-wave (SSBW) devices are acoustic-wave devices, which utilize shear horizontal waves propagating just below the surface of the substrate. Because the wave radiates energy into the bulk of the crystal, the SSBW suffers from a considerable acoustic beam spreading loss. However, this disadvantage can be minimized through coupling of the SSBW with the surface modes either by corrugating the surface region between the transducers or by layering the surface with metallic or dielectric materials [1]–[4]. The effect of these alterations in device construction is to convert the SSBW wave into a guided surface shear-horizontal (SH) wave or Love wave, increasing the coupling coefficient and reducing the insertion loss. The configuration where a shear surface wave propagates in a waveguide consisting of a layer of a shear acoustic velocity (V_L), deposited on a substrate of a shear acoustic velocity (V_S), is known as a Love-plate on an isotropic or anisotropic halfspace and has been extensively analyzed theoretically [5]–[7]. The trapping of the SSBW as a surface SH wave can only occur if the shear acoustic velocity in the layer is smaller than that in the piezoelectric substrate i.e., $V_L < V_S$. The larger the difference between the two acoustic velocities the greater the coupling to a Love wave. However, whilst some studies have been presented on metallic overlayers, dielectric overlayers have found more applications. Among the dielectric overlayers used, fused silica (SiO_2) has been the most popular. SiO_2 satisfies the condition for the existence of a Love wave and since it is a hard elastic material, acoustic losses are very low.

This letter describes a geometry that utilizes a polymer overlayer on top of a SSBW device (Y-cut quartz). Polymers exhibit, in general, much lower shear acoustic velocities than quartz (V_S =3764 m s^{-1}) and, therefore, fulfil the necessary requirement for the guidance of a Love wave. The effects of the polymer-layer thickness on the insertion loss and operating frequency of the composite acoustic devices were assessed experimentally. It was shown that the amount of energy coupled and guided by the polymer film as a surface Love wave increases with increasing film thickness, until a saturation level is reached. The sensitivity of the device with various polymer-layer thicknesses was also tested through application of Langmuir–Blodgett (LB) multilayers. Finally, the transmission of the acoustic wave when a viscous liquid was loaded on top of the polymer layer was studied and viscosity changes were monitored in the range of 1–80 cS.

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II. EXPERIMENTAL RESULTS

A single crystal Y-cut (42.5°) quartz, with a propagation direction perpendicular to x-axis, was used as a substrate to support SSBW's, operating at 110 MHz. The input and output interdigital transducers (IDT's) were patterned by conventional photolithographic techniques. Metal layers were evaporated and comprised a 100 Å chromium flash followed by a 2000 Å gold overlayer. IDT's consisted of 80 pairs with a periodicity of 45 μm and an aperture of 2.93 mm. The IDT centre-to-centre separation was 9 mm and the crystal thickness 0.5 mm. The topside was optically smooth whereas the lower side was roughened. The initial insertion loss was $\sim$ 29 dB and a 96% yield was obtained. The mark to space ratio of the metallization pattern was 1:1. An absorbing tape was placed on the bottom surface of the device in order to minimize scattered bulk waves being detected by the receiving IDT. An HP-4195A Network Analyzer was used to monitor the insertion loss, phase and frequency of the wave. The temperature was kept constant at 22.2±0.1 °C by using a Peltier plate.

A layer of polymethylmethacrylate (PMMA) was applied over the entire transducer and propagation region of the device. PMMA solutions of 5%, 7.5%, 10%, 15%, 20%, 22.5%, and 25% (w/w) were prepared by dissolving PMMA medium molecular weight powder, obtained from Aldrich, in 2-ethoxy-ethyl-acetate (2-EEA). Polymer layers were prepared by spin coating the PMMA solutions over the active surface of the SSBW at 4000 r/min for 40 s. The adhesion of the film was improved by heating the device for 30 min at 150°C. The actual thickness of each film was determined by using a talysurf profilometer. Each PMMA film was removed by sonicating the device in 2-EEA for 10 min, before the new polymer solution was applied on the surface.

PMMA is a soft viscoelastic material with a quite low shear acoustic velocity (V_{PMMA} = 1100m s^{-1}) [8]. For the range of polymer thicknesses studied, only the fundamental, zero-order Love mode was present. The maximum layer thickness (h_o) for monomode operation [5] is given by

$$h_o = \frac{V_S V_L}{2f\sqrt{(V_S^2 - V_L^2)}} \tag{1}$$

which for the PMMA /quartz geometry is 5.1 mm, at the operating frequency (f) of 110 MHz.

Since the acoustic velocity in the overlayer is much smaller than that in the quartz substrate, deposition of the polymer layer results in the conversion of the SSBW to a Love wave. The mode conversion can be followed by monitoring the insertion loss of the acoustic wave. The decrease in the insertion loss, i.e. the signal gain (dB), is given by the difference in the insertion loss between the coated and uncoated SSBW device. As shown in Fig. 1, the signal gain increases with increasing polymer thickness, until a saturation level is reached at a thickness of about 1.2 μm. At that level, the acoustic wave is 8 dB less lossy than the original SSBW signal.

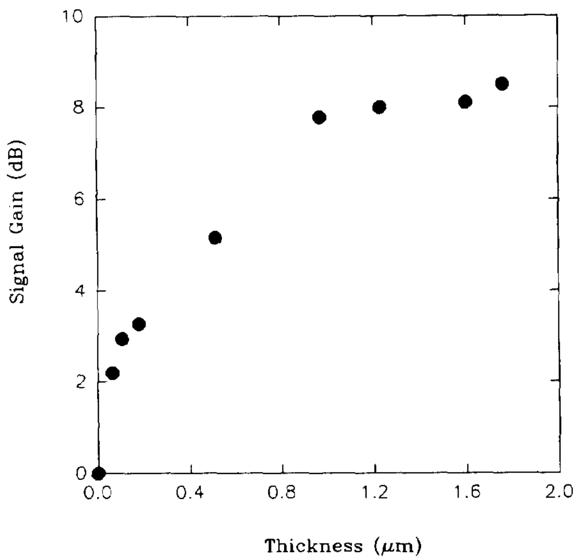

Fig. 1. Signal gain (dB) of the SSBW device when coated with PMMA overlayers of increasing thickness (μm).

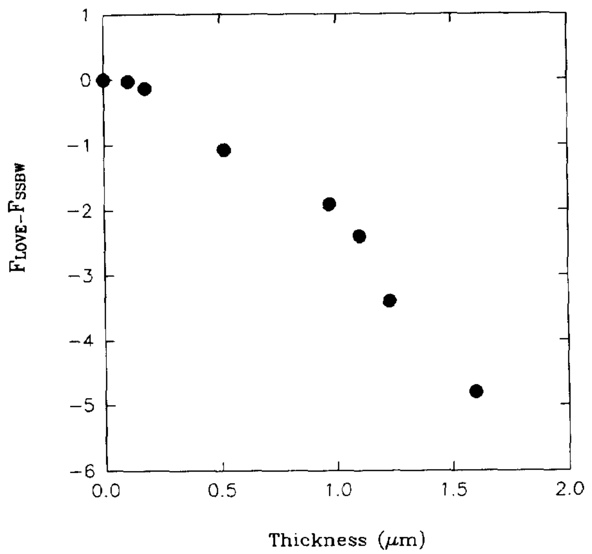

Fig. 2. Frequency drop (MHz) of the PMMA Love-plate device with increasing the PMMA-layer thickness (μm).

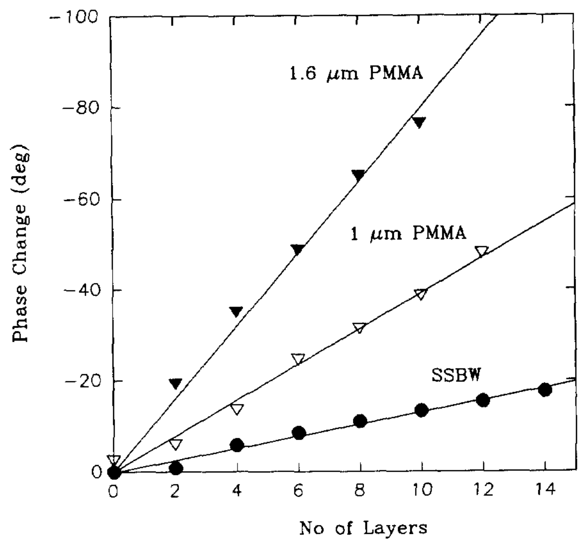

Fig. 3. Phase change as a function of the number of LB layers, for the SSBW, the 1-μm and the 1.6-μm PMMA Love-plate device.

The decrease of the insertion loss results from a redistribution of the acoustic energy, accompanying the mode conversion. Since the Love wave is a surface wave, most of the propagating energy is located in the overlayer and in that part of the substrate close to the interface; consequently, a higher acoustic signal is now detected by the transducer. The reduction of the insertion loss also implies that the wave penetration depth into the quartz is decreased. For small layer thicknesses ($h < 2.5$ μm), the fraction of the total power confined in the layer to that travelling in the substrate is small and attenuation caused by polymer losses is negligible. As the thickness increases, the fraction of the total power guided by the layer is appreciably larger and attenuation in the polymer becomes the predominant mechanism of acoustic loss. For $h \geq 2.5$ μm, the insertion loss of the coated device was found to be even greater than that of the uncoated SSBW device. This suggests that the lossy nature of the polymer film determines the optimum layer thickness of the Love plate and should be taken into account when designing an efficient Love-wave device.

Coating the quartz substrate with polymer layers also resulted in a shift of the operating frequency of the composite acoustic device. Fig. 2 shows the frequency shift as a function of the PMMA-layer thickness. F_{SSBW} denotes the operating frequency of the bare SSBW device and F_{LOVE} is the frequency of the polymer-coated device, where most of the acoustic energy is carried by a Love wave.

The sensitivity of the new configuration was evaluated by depositing multiple LB layers. For preparation of the films, bilayer assemblies of ω-tricosenoic acid were deposited as Y-type layers and a "head-to-head and tail-to-tail" configuration was created. The total mass added to the polymer surface was checked by monitoring the phase change of the Love-plate device operating in air. Fig. 3 shows the phase change as a function of the number of the LB layers for the SSBW, the 1-μm and the 1.6-μm PMMA Love-plate device. According to these results, the 1.6-μm PMMA coated device is 6.6 and 1.9 times more sensitive to mass loading than the bare SSBW and the 1 m PMMA device, respectively. This additional information shows that mode confinement in the PMMA/quartz interface increases with increasing polymer thickness, thereby enhancing the sensitivity.

Further study was focused on the performance of the composite device in contact with a liquid medium. SH surface waves can propagate in a viscous fluid, since viscoelastic theory for monolayers has predicted that viscous liquid surfaces can carry surface shear waves [9]. The only lossy mechanism that operates when a SH wave propagates in a liquid medium is a result of viscous coupling and not of mode conversion and viscous coupling, as in the case of Rayleigh waves. The phase change of the Love wave in contact with a viscous liquid was investigated by applying aqueous glycerol solutions of different viscosities on the polymer surface using a flow cell. Fig. 4 shows the phase change (deg) with the liquid viscosity, for the SSBW the 0.11-μm and the 1-μm PMMA coated device, where phase change denotes the difference between the phase of the Love-plate device in contact with the viscous liquid to the phase of the SSBW device operating in air. The phase decrease observed with all devices shows that the velocity of the acoustic wave decreases as the wave travels in a more viscous liquid. The sensitivity of the Love-plate devices to viscosity changes increased appreciably, compared to that of the bare device. The 1-μm PMMA Love-plate device appeared to be approximately one order of magnitude more sensitive than the SSBW device. The wave velocity reached a saturation level when the

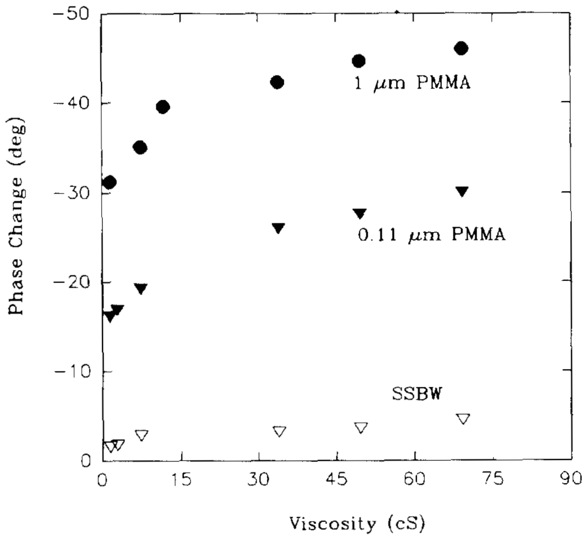

Fig. 4. Phase change as a function of viscosity, for the SSBW, the 0.11-μm and the 1-μm Love-plate devices.

relaxation times in the fluid started becoming longer than the wave period and the liquid started behaving as a solid.

III. Conclusion

Despite much effort up to date, acoustic devices have proved difficult to exploit in chemical sensing. Inherent disadvantages of BAW and SAW devices, such as the low frequency of operation of the former and the normal displacement component of the latter, have limited their applications in liquid media. Devices utilizing shear horizontal waves do not exhibit these problems and their operation in the presence of liquid has already been demonstrated with the SH acoustic plate mode devices [10]–[14]. However, acoustic energy is distributed between the top surface and lower surface of these devices and cannot be concentrated intimately with the surface unless very thin plates are used. Love devices can have thin guiding plates (i.e. overlayers) that concentrate the acoustic energy at the surface, while still remaining physically durable. In addition, the overlayer can provide a versatile selective interface for chemical sensing.

This letter describes a novel acoustic Love-plate device, consisting of a PMMA layer deposited on a SSBW device. It was shown that this composite wave guide configuration enhanced the acoustic signal by 8 dB, through coupling the SSBW to a Love wave and thus increased the sensitivity of the device to mass-loading and viscosity. These observations suggest that the Love-plate may find potential application as a sensitive chemical or immunosensor through coupling appropriate chemical recognition molecules or antibodies to the surface of the polymer overlayer.

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