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On the Fundamental Mode Love Wave in Devices Incorporating Thick Viscoelastic Layers *

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A detailed investigation is presented for Love waves (LWs) with thick viscoelastic guiding layers. A theoretical calculation and an experiment are carried out for LW devices incorporating an SU-8 guiding layer, an ST-90° X quartz substrate and two 28-μm periodic interdigital transducers. Both the calculated and the measured results show an increase in propagation velocity when $h/\lambda > 0.05$. The measured insertion loss of LWs is consistent with the calculated propagation loss. The insertion loss of bulk waves is also measured and is compared with that of LWs.

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Recently a growing number of acoustic wave modes[1−3] have been applied in various fields. Among the modes, Love wave (LW) sensors have been attracting much attention since they were used for bio (chemical) sensing applications.[4,5] The detector of an LW based sensor consists of a semi-infinite piezoelectric substrate which supports shear horizontal (SH) waves, a guiding layer in which the transverse acoustic wave is slower than that in the substrate, and interdigital transducers (IDTs) which are deposited on the substrate surface for exciting and receiving SH waves. The maximum sensitivity has been proved, occurring at the maximum slope of the dispersion curve. To achieve a higher sensitivity, LW devices have been reported[6,7] incorporating guiding layers consisting of polymeric materials which have slower transverse waves and lower density than the commonly used silicon dioxide. Due to the viscoelasticity of polymers, most developed LW devices incorporate guiding layers that are much thinner than the optimum thickness. Only McHale *et al.*[8] and Newton *et al.*[9] carried out experimental study on the resonant conditions and insertion loss changes of LW devices with thick S1813 photoresist layers on ST-cut quartz substrates. In their experiments, the first higher order mode LW was found, occurring at the relative layer thickness of $h/\lambda = 0.06$, which is much thinner than the theoretical thickness. To the best of our best knowledge, there is still no reasonable theoretical explanation for this abnormal phenomenon.

In this Letter, we present a detailed investigation on LW devices with thick viscoelastic guiding layers. A theoretical calculation is carried out for LW devices incorporating an SU-8 guiding layer, an ST-90° X quartz substrate and two 28-μm periodic IDTs. The experimental devices are fabricated and measured. The calculated velocity agrees well with the measured result and it shows that the guiding layer viscoelasticity causes an increase in the LWs propagation velocity. The insertion loss of LWs is measured, which is consistent with the calculated propagation loss. The insertion loss of bulk waves (BWs) is also measured and is compared with that of LWs. The results and discussions presented in this work will be helpful in analyzing and optimizing the performances of LW based sensors incorporating polymeric layers.

The substrate of an LW device must be a material which supports pure piezoelectric SH acoustic waves.[10,11] The most commonly used substrate is ST-cut quartz, which has a tiny piezoelectricity and an obvious anisotropy, thus it can be considered as an anisotropic medium. The guiding layer is an isotropic material which is coated on the substrate surface with a thickness of h. The dispersion equation[12] of LWs in such a structure is

$$\mu_L \beta_L \tan(\beta_L k h) = c_{44} \overline{\beta_S}, \quad (1)$$

where $k = \omega/v$ is the propagation factor of LWs, ω is the angular frequency, v is the propagation velocity, $\beta_L = \sqrt{v^2/(V_L)^2 - 1}$ is the particle displacement distribution factor in the guiding layer, $V_L = \sqrt{\mu_L/\rho_L}$ is the phase velocity of transverse acoustic waves in the layer, μ_L and ρ_L are the shear modulus and density of the guiding layer, respectively, $\overline{\beta_S} = \sqrt{(V_{S1}^2 - v^2)/V_{S2}^2}$ is the real part of the distribution factor in the substrate, $V_{S1} = \sqrt{(c_{66} - c_{46}^2/c_{44})/\rho_S}$ is the velocity of quasi-SH waves propagating in the same direction to LWs, $V_{S2} = \sqrt{c_{44}/\rho_S}$ is the velocity of SH-polarization and propagating in the vertical direction, c_{44}, c_{46} and c_{66} are elastic constants of the substrate, and ρ_S is the density of the substrate.

Different from elastic overlays, a polymer guiding layer will produce a large propagation attenuation due

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to its non-ignorable viscosity. When the viscoelasticity is included, the shear modulus μ_L of the guiding layer becomes a complex variant. The mechanical behavior of a viscoelastic material can be described by using the Maxwell–Weichert model[13] consisting of springs and dashpots. In this work, a simplified model incorporating an elastic branch and a Maxwell branch is adopted. Thus the complex shear modulus can be expressed as

$$\mu_L = \mu_0 + \mu_1 \frac{i\omega\tau_1}{1+i\omega\tau_1}, \tag{2}$$

where $\tau_1 = \eta_1/\mu_1$ is the relaxation time of the Maxwell branch, μ_0 and μ_1 are elastic constants of the elastic branch and the Maxwell branch respectively, and η_1 is the viscosity of the Maxwell branch. Substituting the complex μ_L into the dispersion equations, we can obtain a complex velocity $v = v_r + iv_i$. Here v_r represents the propagation velocity in the x_1 direction, while v_i is related to the propagation loss in the x_1 direction. The insertion loss (IL) reads

$$\mathrm{IL} = 20\log_{10} e^{\mathrm{Im}(\omega/v)} \approx -54.6\frac{v_i}{v_r}. \tag{3}$$

The LW devices used in our experiments consist of an ST-cut and 90° X-propagation quartz substrate with two lithographically defined Al (200 nm) IDTs. The IDTs are of aperture 2 mm and separated by a path length (center to center distance) of 4 mm. Each IDT consists of 72 periods of split-electrodes, with a wavelength of $\lambda = 28$ μm (3.5 μm electrode widths and spacings).

A guiding layer was deposited on the device surface by spin coating a solution of SU-8 2050 (with a volume ratio of 1:3 to the diluent agent), where a negative epoxy-based photoresist was obtained with MicroChem equipment. To achieve different layer thicknesses, we took the rotating speed ranging from 1000 to 5000 rpm and different spinning times, and the layer was post-cured by heating the device for 30 min at 150℃. The film on the wire pad was removed by using a sharp scalped blade. The thickness of the prepared SU-8 layer was measured by using an Alpha-step IQ surface profiler (KLA-Tencor, San Jose, CA). The coated wafer was divided into several LW devices. Then each device was mounted on a rectangular DIP header with electrical connections made by Al wires bonding. The input and output impedances of the Love device were matched to around 50 Ω by using LC circuits. Two SMA connectors were applied to connect the device and an HP8753D network analyzer.

Figure 1 shows the frequency response S_{21} of the LW device covered a 0.74-μm-thick SU-8 guiding layer. There are two obvious signals. One is located at the frequency of 177.0 MHz (the corresponding propagation velocity of 4956.6 m/s), which is caused by the fundamental mode of LWs. The insertion loss of LWs is of about 10 dB. Another signal is distributed between 182–191 MHz (the corresponding propagation velocity of 5096–5348 m/s), which is probably caused by bulk waves. The insertion loss of bulk waves is about 30 dB.

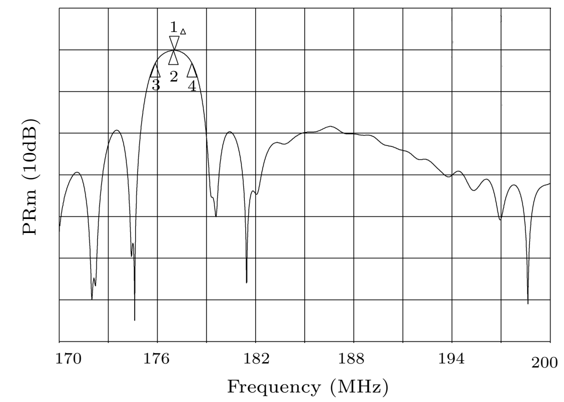

Fig. 1. Frequency response of the LW device coated with a 0.74-μm-thick SU-8 layer.

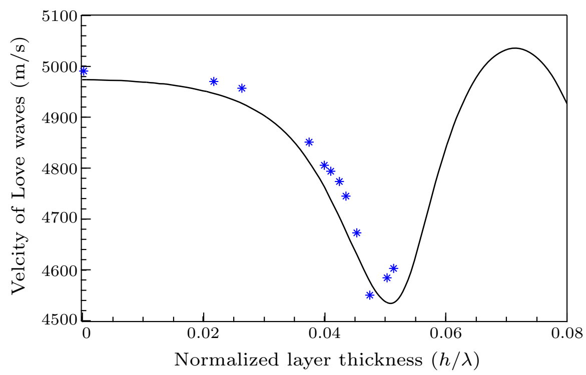

Fig. 2. Theoretical and experimental velocities of the fundamental Love mode.

Figure 2 shows the calculated (solid line) and measured (stars) propagation velocities as a function of the normalized layer thickness (h/λ). In the numerical calculations, the material parameters of the substrate (ST-90° X quartz)[12] are assumed: the elastic constants of $c_{66} = 67.47$ GPa, $c_{44} = 30.34$ GPa, $c_{46} = -7.60$ GPa, and the density of $\rho = 2651$ kg/m^3; the parameters of the guiding layer (SU-8) are assumed: $\mu_0 = 0.94$ GPa, $\mu_1 = 0.71$ GPa, $\tau_1 = 0.9$ ns, and $\rho_L = 1215$ kg/m^3. As shown in Fig. 2, initially the propagation velocity is slowly reduced by increasing the guiding layer thickness. During the calculations, the substrate piezoelectricity is ignored, which will cause a reduction of ∼20 m/s in propagation velocity of the fundamental Love mode;[12] therefore the theoretical velocity is lower than the experimental values.

When h/λ exceeds 0.03, the velocity reducing is sped up, which is proved in an optimum region to achieve a large mass loading sensitivity. When h/λ exceeds 0.05, the reducing is decreased rapidly and even a raising velocity is obtained as the layer is further thickened. The theoretical velocity can reach up to 5050 m/s at $h/\lambda = 0.07$, which is equivalent to the velocity of SSBW in the substrate. This result coincides with some previously reported experimental results.[8,14]

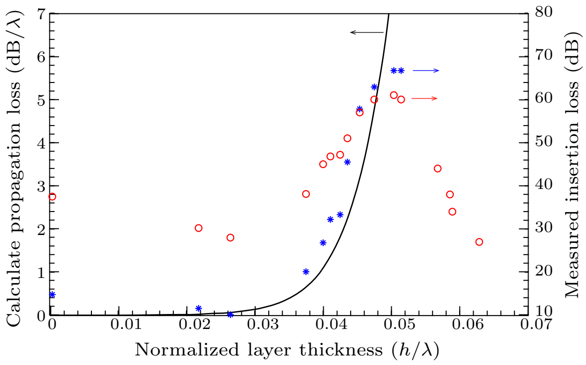

Fig. 3. Theoretical propagation loss (solid line) of the fundamental Love mode and measured insertion loss of LWs (asterisks) and BWs (circles).

For a Love device, the insertion loss is decided by IDT structures, the electromechanical coupling factor and the propagation loss, which is caused by the viscosities of the guiding layer and the substrate. In this work, the substrate is considered as an elastic material, thus the propagation loss is mainly caused by the polymeric guiding layer. Figure 3 shows the calculated propagation loss (solid line) of the fundamental Love mode, the measured insertion loss of LWs (asterisks) and bulk waves (circles). As the guiding layer is thickened, the calculated propagation loss is always being increased. When $h/\lambda < 0.03$, the propagation loss is relatively small and increased very slowly; thus the device insertion loss is mainly decided by the electromechanical coupling factor rather than the propagation loss. As mentioned in previous reports, the electromechanical coupling factor is initially increased with thickening the guiding layer and is seldom affected by the viscosities of guiding layers. Therefore, the measured device insertion loss is decreased with thickening the guiding layer. When $h/\lambda > 0.03$, the propagation loss is increased at an increasing speed with thickening the guiding layer; the attenuated acoustical energy caused by increasing propagation loss exceeds the increased energy produced by enlarging the electromechanical coupling factor. Therefore, the insertion loss of LWs is increased when the guiding layer is further thickened. As $h/\lambda > 0.05$, the propagation loss is increased at an accelerating rate while the electromechanical coupling factor starts to be decreased, thus the device insertion loss is increased very rapidly and soon the signal of LWs is too weak to be detected.

The insertion loss of bulk waves is shown by circles in Fig. 3. When $h/\lambda < 0.05$, the insertion loss of bulk waves is also first decreased and then increased, which is similar to that of LWs. When $h/\lambda > 0.05$, the insertion loss is quickly increased with thickening the guiding layer. It should be noted that when $h/\lambda > 0.043$, the insertion loss of bulk waves is less than that of LWs. This phenomenon is easily misunderstood as the start of the first higher order Love mode. In fact, the theoretical starting layer thickness[15] is $h = \frac{\lambda}{2\sqrt{V_S^2/V_L^2-1}} \approx \frac{\lambda}{9}$.

In conclusion, we have shown a detailed investigation on LW devices incorporating a thick viscoelastic guiding layer. When the relative guiding layer exceeds 0.05, the theoretical result shows that the viscoelasticity causes an increase in the propagation velocity of LWs, and the result is confirmed with the experimental devices. The insertion losses of LWs and bulk waves are also measured and analyzed. The calculated propagation loss is consistent with the measured insertion loss of LWs. The results and discussions presented in this work will be helpful in analyzing and optimizing the performances of LW based sensors incorporating polymeric layers.

References

[1] Kim C and Jhang K 2012 *Chin. Phys. Lett.* **29** 120701
[2] Khaled S M, Soliman R K and Sara I A 2013 *Chin. Phys.* B **22** 124702
[3] Tan F and Huang X 2013 *Chin. Phys. Lett.* **30** 050701
[4] Gizeli E, Stevenson A C, Goddard N J and Lowe C R 1992 *IEEE Trans. Ultrason. Ferroelectr. Freq. Contr.* **39** 657
[5] Kovacs G, Lubking G W, Vellekoop M J and Venema A 1992 *IEEE Ultrason. Symp. Proc.* (Tucson Arizona, USA 20–23 October 1992) p 281
[6] McHale G Newton M I and Martin F 2003 *J. Appl. Phys.* **93** 675
[7] Matatagui D, Fernández M J, Fontecha J, Sayago I, Gràcia I, Cané C, Horrillo M C and Santos J P 2014 *Talanta* **120** 408
[8] McHale G, Newton M I, Martin F, Gizeli E and Melzak K A 2001 *Appl. Phys. Lett.* **79** 3542
[9] Newton M I McHale G and Martin F 2004 *Sens. Actuators* A **109** 180
[10] Jakoby B and Vellekoop M J 1997 *Smart Mater. Struct.* **6** 668
[11] Liu J and He S 2010 *Int. J. Solids Struct.* **47** 169
[12] Liu J 2014 *AIP Adv.* **4** 077102
[13] Liu J, Wang L, Lu Y and He S 2013 *Smart Mater. Struct.* **22** 125034
[14] Penza M and Cassano G 2000 *Sens. Actuators* B **68** 300
[15] Zimmermann C, Rebière D, Déjous C, Pistré J, Chastaing E and Planade R 2001 *Sens. Actuators* B **76** 86

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