Point contact ultrasonic transducer of waveguiding structure for high-frequency operation

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This letter presents a new type of Hertzian-contact transducer of waveguiding structure operating in the MHz range. The transducer is composed of a fused quartz tube and a radially-polarized annular piezoelectric element bonded to one of its ends. The edge-bonded shear-wave transducer effectively excites a surface wave on the interior surface of the tube. A small bullet pin made of quartz is inserted and fixed on the other end of the tube to make a point contact and transmit the wave energy to a specimen to be inspected. Using a pair of these transducers, we have succeeded in exciting and detecting surface acoustic waves as well as Lamb waves in the 3 MHz frequency range. © *1996 American Institute of Physics.* [S0003-6951(96)03010-7]

Hertzian-contact pin transducers have been used for the excitation and detection of Lamb waves in plates.[1,2] As shown in Fig. 1, the transducer is composed of a piezoelectric cylinder combined with a buffer rod whose end is sharpened like a pin to make a point contact to a solid plate.[2] Time-of-flight measurements with these point-like contact transducers have successfully been applied for the detection of anisotropy, and for *in situ* measurements of film thickness and temperature.[2] For measuring surface wave velocities and/or evaluating thickness of very thin films on a substrate, the transducers need to be operated at higher frequencies such as the MHz range. However, the operating frequency range of the pin transducers so far was actually restricted to several hundreds of kHz. This was because the diameter of the buffer rod had to be designed to be a few times smaller than the wavelength so that it would vibrate in a single, low dispersive length-extensional mode. This restriction on the wavelength-to-diameter ratio brought about difficulties in fabricating pin transducers suitable for high frequency operation.

The new transducer configuration proposed here is shown in Fig. 2. The transducer employs a waveguiding tube[3,4] instead of a rod at the buffer section, and a radially-polarized annular piezoelectric element bonded to one end of the tube. The edge-bonded shear-wave transducer will effectively excite a surface wave on the interior surface of the tube. A small bullet pin is inserted and fixed on the other end of the tube, and it makes a point contact to the specimen to be inspected. The interior surface wave on the tube will be converted to an exterior surface wave on the bullet pin at the tube-pin boundary, and the wave energy will be transmitted to the specimen.

Transducers were fabricated using fused quartz tubes of inner diameter $2a=3.6$ mm, outer diameter $2b=10$ mm, and length $l=100$ mm as the buffer. Annular plates of PZT-5H having inner diameter of 3.6 mm, outer diameter of 9.6 mm, and thickness of 0.27 mm were bonded to one end of the tubes. The plate polarized in the radial direction was designed to have a center frequency at around 3.6 MHz. It has been known that a shear wave transducer bonded to a 90° edge of a substrate (edge-bonded transducer) excites a surface acoustic wave (SAW) efficiently if the electrode depth is set to about one wavelength of the SAW to be launched.[5] Since the wavelength of the interior SAW was estimated to be 0.96 mm at 3.6 MHz, an annular electrode of 1 mm width was deposited on the inner end of the top surface of the PZT, whereas full metalization was made on the bottom surface.

Phase velocity dispersion curves for symmetric modes in a fused quartz tube are shown in Fig. 3 for b/a of 2.78.[6] Here, the horizontal axis is the product of frequency f and the inner radius a. For large fa, the first and the second branches become the exterior and the interior surface wave modes, respectively.[4] The interior surface wave velocity is 3457 m/s at 3.6 MHz ($fa=6.48$ MHz mm) and the velocity dispersion seems to be small around this frequency.

First, some experiments were made to confirm SAW-to-SAW conversion at the tube-pin boundary. Two tubes were placed with their ends facing each other, and a fused quartz rod of 40 mm length was inserted in between them. The rod had the same diameter (3.6 mm) as the hole of the tubes, so that it fitted well in the tubes. A small amount of water was put into the boudary by capillary action.

The optimum coupling length L in this case may be

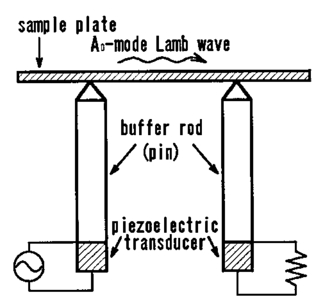

FIG. 1. Time-of-flight measurement system with point-contact transducers.

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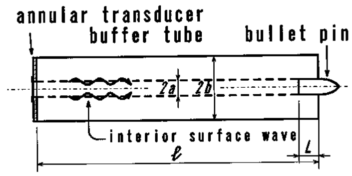

FIG. 2. New configuration of point-contact transducer composed of waveguiding tube and bullet pin.

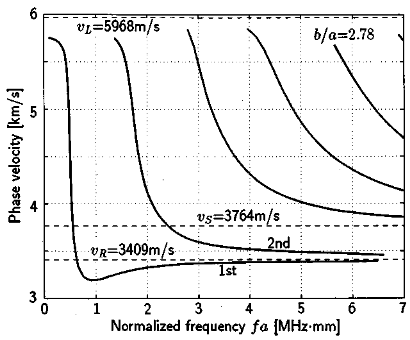

FIG. 3. Phase velocity dispersion curves for symmetric modes in a fused quartz tube for $b/a=2.78$.

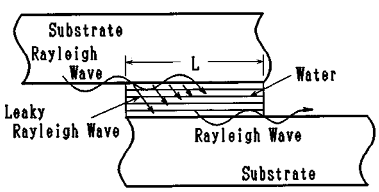

FIG. 4. Mode conversion at two plane boundaries partially filled with water.

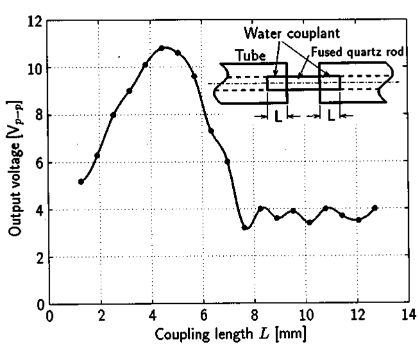

FIG. 5. Variation of transmitted signal intensity for tube-rod-tube configuration.

estimated using a simple model as follows: Suppose that two plane surfaces of a same material are facing each other across a uniform gap, one section of which is filled with water over the length L as shown in Fig. 4. A surface wave propagating on the upper plane will leak its energy into the water at the water-loaded section. The longitudinal wave in

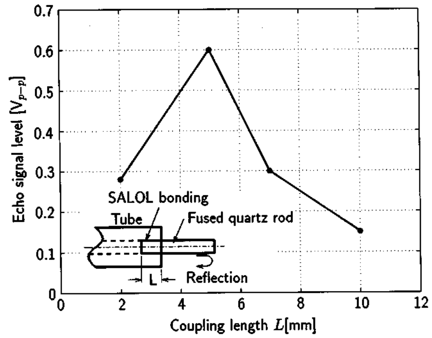

FIG. 6. Variation of the signal intensity reflected back from the rod end. The rod is bonded to the tube with SALOL.

the water will impinge on the other surface at the Rayleigh angle and will be converted again into a surface wave. The propagation constant k_{LSAW} for the leaky surface wave can be written as

$$k_{\mathrm{LSAW}}=\frac{2\pi}{\lambda_{\mathrm{LSAW}}}(1+j\alpha_N)\equiv\beta+j\alpha, \tag{1}$$

where β and α are the phase and attenuation constants, respectively, λ_{LSAW} is the wavelength of the leaky SAW, and α_N is the normalized attenuation constant. It has been reported that the mode conversion will be optimum at $\alpha L\approx 1.26$.[7–9] Applying $\alpha_N=3.82\times 10^{-2}$ for the quartz/water boundary,[10] L is evaluated at the frequency of 3.6 MHz as follows:

$$L=\frac{1.26}{\alpha}=1.26\bigg/\left(\frac{2\pi\alpha_N}{\lambda_{\mathrm{LSAW}}}\right)\approx 5[\mathrm{mm}]. \tag{2}$$

Figure 5 shows the variation of the transmitted signal intensity versus the coupling length L for the tube-rod-tube configuration measured at 3.575 MHz. Maximum transmission is obtained at $L\approx 5$ mm, as predicted theoretically.

Next, we examined the optimal value for L by a pulse-echo method when the rod was fixed to the tube. The rod was inserted and bonded with SALOL (phenyl salicylate) to the end of the tube, and the echo signal from the end of the rod was observed. Figure 6 shows the variation of the signal level versus the coupling length L. It is seen that, although the data points are few, maximum reflection is obtained at $L=5$ mm.

The theoretical model illustrated in Fig. 4 assumes a

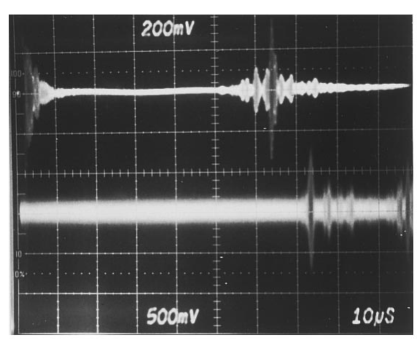

FIG. 7. Signal waveforms obtained for a glass block. Upper trace is at the transmitter and lower one at the receiver.

coupling layer having the thickness of a few wavelengths or more. The experimental results in Figs. 5 and 6 may imply that the model is appropriate even for the case that the layer is very thin.

Based on the experimental results described above, bullet pins were designed and fabricated. The pin had a diameter of 3.6 mm, a length of 13 mm, and an apex angle of about 60°. The top of the pin was polished and rounded to a radius of curvature of 100 μm. The pin was inserted into the tube a distance of 5 mm and fixed with SALOL.

Some preliminary experiments of transmission and reception of guided waves were made using a pair of such transducers. A 76.2 mm diameter silicon wafer of 0.4 mm thickness and a glass block of 97 mm diameter and 17.3 mm thickness were employed as samples. The transducer pins were separated from each other by 26.7 mm and pressed gently against the samples. The exterior surfaces of the tubes were covered with clay to suppress unwanted modes. The transducer was excited with an RF-pulse voltage having a center frequency of 3.360 MHz and a length of 1 μsec.

As an example, signal waveforms observed for the glass block are shown in Fig. 7. The upper trace is the signal at the electric port of the transmitter and the lower one is that at the receiver. The first arrival of the received signal was confirmed to be a SAW response because it faded away when a water drop was put on the transmission path. With the new type of point-contact transducers we have succeeded in the excitation and detection of SAWs which had been difficult with low-frequency point-contact transducers.

In conclusion, a new type of dry contact transducer for high-frequency operation has been developed. The transducer utilizes a waveguiding tube at the buffer section that carries a SAW on its interior surface. The interior SAW is converted into a SAW propagating on the exterior surface of a bullet pin that is making a point contact to a sample to be examined. With a pair of transducers we have succeeded in the excitation and detection of surface acoustic waves on a glass block as well as Lamb waves on a silicon wafer at a frequency of 3.36 MHz.

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