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Wideband high-frequency line-focus PVDF transducer for materials characterization

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Abstract

This paper presents the design, fabrication, operating characteristics and applications of a wideband, high-frequency, line-focus beam transducer we constructed using a 9 μm thick piezoelectric polyvinylidene fluoride (PVDF) film. This transducer possesses a focal length of 2.38 mm and an aperture angle of 84°. The frequency spectrum of the signal measured at the focal point indicates that the transducer has a wide frequency response which extends from 10 MHz to over 100 MHz. When compensated for the frequency-dependent attenuation of the coupling medium, the operational frequency exceeds 150 MHz. The transducer can be operated in a time-resolved pulse mode or in a radio-frequency (rf) tone burst mode. An application of the transducer to determine the anisotropic elastic property of a silicon wafer is demonstrated. The phase velocities of surface acoustic waves (SAW) propagating along various directions on the (0 0 1) surface of cubic silicon are measured and compared to computed values.

1. Introduction

In acoustic microscopy, line-focus transducers have been widely used for quantitative materials characterization [1–3]. The line-focus transducer, unlike the point-focus unit [4–7,11], can launch surface acoustic waves (SAW) in a specific direction, which is perpendicular to the focusing line. This is particularly useful for study of the anisotropic properties of materials. In conventional acoustic microscopes, the high-frequency transducer is mounted on the flat side of a buffer rod, which is typically made of sapphire or quartz. The opposite side of the buffer rod is shaped into a concave spherical or cylindrical shape so that the acoustic beam emerging from the buffer rod converges through a coupling fluid into a focal spot or line. Because of the pronounced differences between the acoustic impedances of the transducer, buffer rod, and coupling medium, the conventional design suffers from significant energy loss in the transmitted acoustic beam. The design also suffers from geometrical aberration of the focusing beams.

To alleviate the problems associated with the conventional design of acoustic lenses, Lockwood et al. [8] and Smolorz and Grill [9] chose a different design, in which a flexible polyvinylidene fluoride (PVDF) piezoelectric polymer film was attached onto a spherically shaped epoxy surface whose radius of curvature determines the distance of the focal point, devoid of geometrical aberration. Because of a relatively smaller mismatch of acoustic impedances (2.3–1) between the PVDF material and the water coupling medium, acoustic energy is more efficiently coupled into a specimen [12]. Lockwood et al. [8] used their transducer in a pulse mode operation, while Smolorz and Grill used their transducer of similar design in the radio-frequency (rf) burst mode. Xiang et al. [3,13] attached a 28 μm thick PVDF foil on the cylindrical surface of an impedance matching backing material consisting of epoxy and tungsten powder. They obtained a line-focus acoustic transducer of 25.4 mm focal length and a bandwidth centered around 10 MHz. They operated their line-focus transducer in the pulse mode.

We describe here the design of PVDF line-focus transducer, which is a hybrid of Refs. [3,8,9]. It includes a better backing material of non-polarized PVDF and a thin 9 μm piezoelectric PVDF film as the active element. We will show the broad and high frequency response

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and the spatial resolution of this transducer as well as its applications with either pulse or rf burst excitations.

2. Line-focus transducer design

The material used for construction of the line-focus transducer is a 9 μm thick piezoelectric PVDF polymer film, which was manufactured by AMP company. The front and back sides of the film were deposited with an approximately 60–70 nm layer of gold and copper electrodes, respectively. The PVDF foil is sliced into a strip that is 30 mm in length and 6.35 mm in width. Then the outer portion of the rectangular copper electrode is chemically etched away, leaving its central rectangular portion intact that is 10 mm long and 3 mm wide.

The backing material chosen is the same PVDF material, but it is unpoled and non-piezoelectric. It has the same acoustic impedance as that of the piezoelectric PVDF film. The PVDF backing block was initially cut into a cylindrical block that is 16 mm long with a 9.52 mm square cross-section. As shown in Fig. 1, the central portion of the transducer side of the block is shaped into a cylindrical arc of 2.38 mm radius with a chord length of 3.18 mm, subtending an angle of 84° when viewed from the center of the arc. Both left and right portions surrounding the cylindrical arc of the PVDF backing block are faced at a 42° angle with respect to the horizontal. Two symmetrically located brass pins through the backing block provide electrical connections.

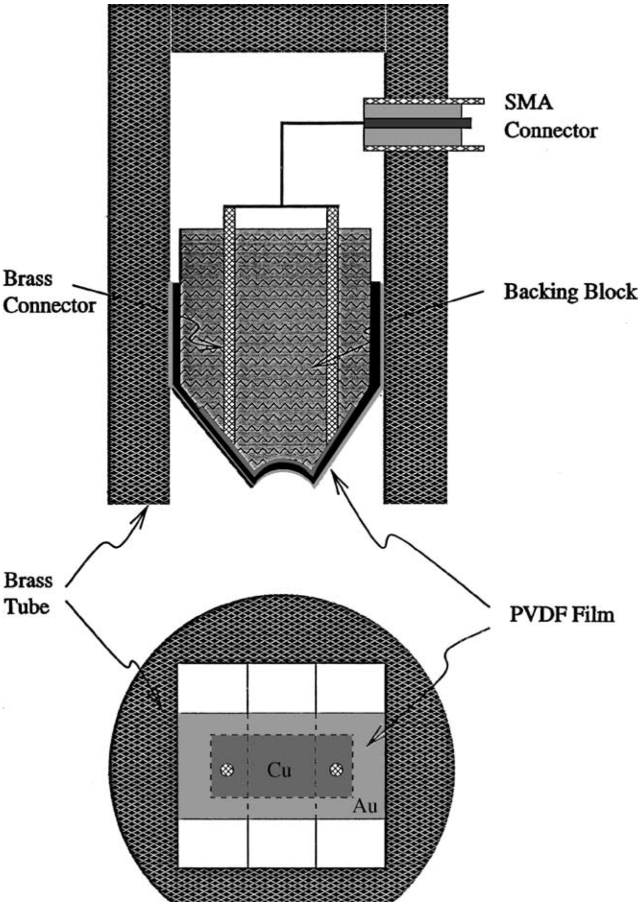

Fig. 1. Schematics of the cross-section of the assembly of a PVDF line-focus transducer.

The chemically etched piezoelectric PVDF film is then attached to the backing PVDF block using a thin layer of epoxy as an adhesive. The copper electrode side of the film faces towards the cylindrical arc of the backing block and makes electrical contact with the brass pin electrodes to which exciting electrical signals are applied. The PVDF film conforms to the shape of the backing block, extending midway up the sidewall of the block. Finally, the PVDF transducer film and its backing block are inserted inside a brass tube, which comes in contact with the gold electrode of the PVDF film and serves as ground.

Distilled water is used as the coupling medium between the transducer and the specimen. The ultrasonic signals generated by the piezoelectric PVDF transducer are transmitted through water into the specimen located below. Some of these signals are reflected back to the same transducer, which also acts as a detector. A detailed electronic block diagram of the generation and detection of the ultrasonic signals is described in the next section.

3. Electronic circuit

An overall electronic block diagram for ultrasonic components of the line-focus Scanning Acoustic Microscope (SAM) system is shown in Fig. 2. In the rf-burst mode of operation we used an electronic signal generator capable of generating both continuous and

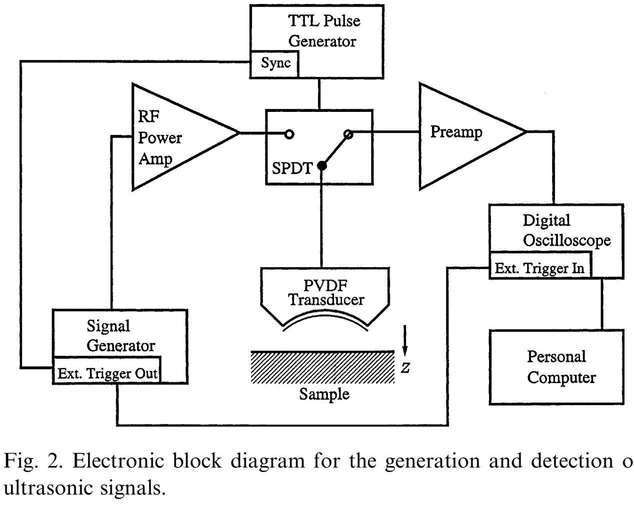

Fig. 2. Electronic block diagram for the generation and detection of ultrasonic signals.

gated harmonic signals with a frequency range of 5 kHz to 1.5 GHz. The gated pulse width we have used was less than 1 μs wide and the gate pulse repetition rate was less than 5 kHz. The rf burst electronic signals derived from the signal generator are input to a rf power amplifier whose output is fed into one port of a single-pole, double-throw (SPDT) switch that is always connected to the PVDF transducer. The other port of the SPDT switch is in contact with the input of a preamplifier whose bandwidth extends from DC to over 300 MHz.

The operation of the SPDT switch is controlled by a TTL pulse generator that is synchronized with the rf signal generator. The switching time of the SPDT switch is less than 20 ns. During the time when the rf gate is on, the SPDT switch is connected to the rf power amplifier and the PVDF film transducer generates ultrasonic signals. When the rf gate is off, the SPDT switch and therefore the transducer are connected to the input of the preamplifier. The output of the preamplifier is connected to a digital sampling oscilloscope capable of digitizing the ultrasonic waveforms at a maximum sampling rate of 5 GHz with 8-bit resolution. The digitized waveforms can be transferred into a high-speed computer for subsequent processing and storage.

When the transducer is operated in the time-resolved pulse mode, a broadband pulse generator generating short-duration pulses was used. The pulse bandwidth centered around 200 MHz and the pulse repetition rate was less than 1 kHz. The excitation amplitude was approximately 12 V.

4. Frequency response and spatial resolution

The frequency response of line-focus PVDF transducer was determined under rf burst mode excitation. A glass plate specimen placed at the focal plane with water as a coupling medium served as a reference reflector. The measured amplitudes of the signals reflected from the specimen as a function of excitation frequency are marked with circles in Fig. 3. The results show a reasonably flat amplitude response with a bandwidth as specified by the -3 dB points, that extended from 10 to 100 MHz. To remove the effects of the water coupling, the measured ultrasonic amplitudes were adjusted to compensate for the frequency-square f^2 increase in ultrasonic attenuation in water [10]. Using the attenuation coefficient $\alpha = 2.53 \times 10^{-14}$ $(f^2\,\mathrm{s}^2)$/m at 20 °C [10], the compensated amplitude spectrum broadens, extending the frequencies well above 150 MHz with a maximum at 110 MHz. The results are depicted with triangles in Fig. 3.

In the line-focus PVDF transducer, in which the active element is shaped into a circular arc, the generated ultrasonic signals converge directly in the focal line, regardless of the operating frequency. This design eliminates all aberration and diffraction problems associated with conventional line-focus transducers. To determine the spatial amplitude distribution in the focal plane, the emitted ultrasound is reflected from a thin line reflector target that is realized by using the edge of a sharp razor blade tip located in the focal plane and oriented parallel to the focal line direction. These measurements were made using the broadband pulse excitation. Fig. 4 shows the detected signal amplitude, as the acoustic axis of the transducer moves perpendicular across the tip of the razor blade. The normalized amplitude profile has an approximately Gaussian dependence on the lateral displacement. The full-width at half-maximum (FWHM) of the Gaussian profile is about 31 μm, which is taken as a measure of the lateral spatial resolution of this line-focus PVDF transducer.

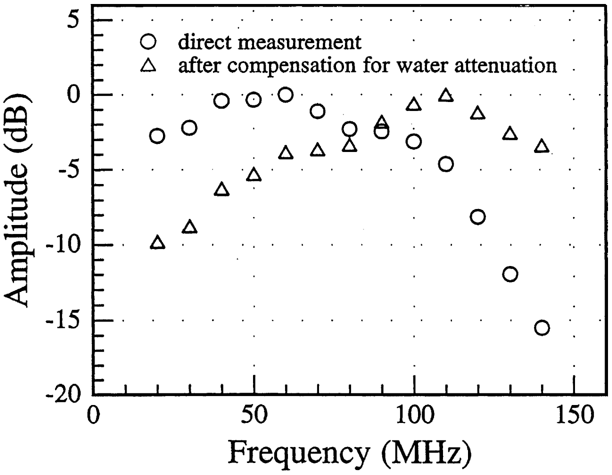

Fig. 3. Frequency response of the PVDF transducer.

When the transducer is detecting reflected signals from a perfect reflector, the amplitude of the receiving

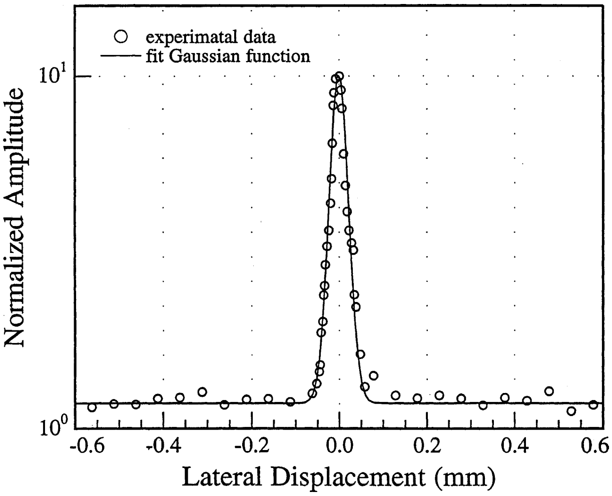

Fig. 4. Normalized amplitude versus lateral displacement with a line reflector located at the origin in the focal plane.

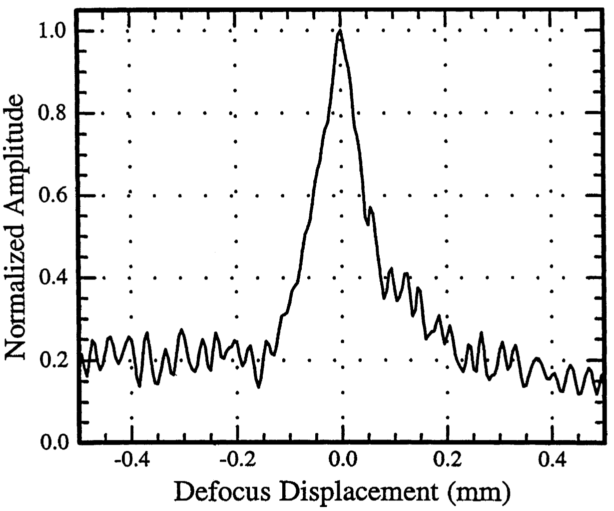

Fig. 5. Amplitude distribution along the acoustic axis with origin at the focal plane. A positive displacement means a larger separation between a specimen and a transducer.

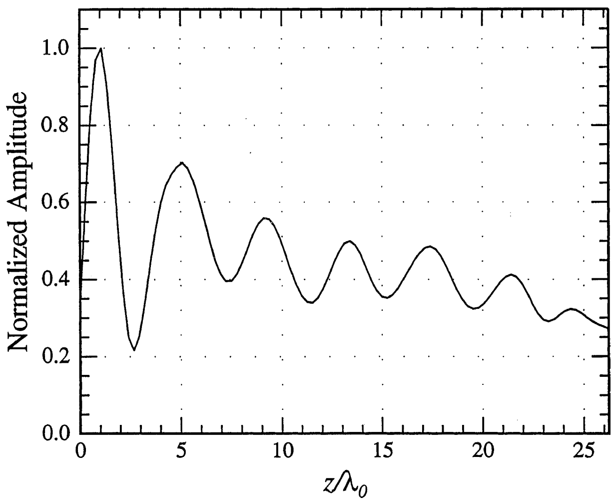

Fig. 6. Measured $V(z)$ curve for a glass slide specimen at 80 MHz. The wavelength of ultrasound in water λ_0 is 18.68 μm at 80 MHz.

signals depends on the defocus distance z between the reflector and the transducer. This dependency is usually denoted as $V(z)$ curve. A block of plexiglass was used as such a perfect reflector. The 5 mm thickness of plexiglass is sufficient to minimize any wave interference between the reflected signals from front surface and those arriving from the back wall. The surface acoustic wave velocity in plexiglass is less than that of water and therefore there is no SAW excitation. Some interference of the lateral longitudinal waves arises when the incident angle exceeds 34°. But the half-angle of the aperture of the PVDF transducer described here is 42°. Therefore the contribution of the lateral longitudinal waves to a total reflection is expected to be small. The result is shown in Fig. 5. There is a sharp peak at the focus where all the acoustic energy is focused and specularly reflected. The amplitude decreases a short distance away from the focal plane. The small ripples in Fig. 5 may arise from the interaction between the edge wave and the specular reflection, as observed by Smolorz and Grill [9].

5. Measurement of acoustic properties of materials

The line-focus transducer can be used to characterize the mechanical properties of both isotropic and anisotropic materials. When the transducer is excited by a tone burst, the sound velocity and attenuation can be determined from analysis of the measured $V(z)$ curve. As noted previously, the $V(z)$ curve is a record of the transducer voltage output with distance z along the acoustic axis when the transducer is driven by a gated harmonic signal. The positive z-direction is taken downward from the focal plane away from the transducer. Variations in the $V(z)$ curve are mainly the result of the interference between the specular rays reflected from the sample surface and leaky SAW rays excited at the water-specimen boundary. The SAW phase velocity of a material can then be determined from the periodicity of $V(z)$ curve [1,11]. Fig. 6 shows the $V(z)$ curve obtained at 80 MHz using a glass microscope slide as a test specimen. In this figure, λ_0 is 18.68 μm corresponding to the wavelength of the ultrasonic wave in water at 80 MHz. The SAW velocity can be evaluated from the equation [1,11]

$$V_R = \frac{\sqrt{V_W f \Delta z}}{\sqrt{1 - V_W/(4f\Delta z)}}, \tag{1}$$

where V_W is the wavespeed in water, f is the frequency of the gated harmonic signal, and Δz is the periodicity of the $V(z)$ curve. Using $\Delta z = 0.0710$ mm measured from Fig. 6 and $V_W = 1495.0$ m/s measured at room temperature, the V_R of the glass slide specimen is determined to be 3009.0 m/s.

The wide bandwidth of the transducer makes it especially suitable for use in the time-resolved pulse mode. When operating in this mode, the specular reflection and SAW arrivals can be directly identified from the recorded signals. Fig. 7 shows an obtained waveform from a thick glass sample at a defocus distance of 0.75 mm. Let τ denote the time interval between the SAW arrival R and the specular reflection arrival D. τ varies linearly with the defocus distance z. The SAW velocity V_R is expressed as [3]

$$V_R = \left[\frac{1}{V_W m} - \frac{1}{4m^2}\right]^{-1/2} \tag{2}$$

where m corresponds to $\mathrm{d}z/\mathrm{d}\tau$.

An example of leaky SAW velocity measurements in an anisotropic material is shown in Fig. 8. To obtain

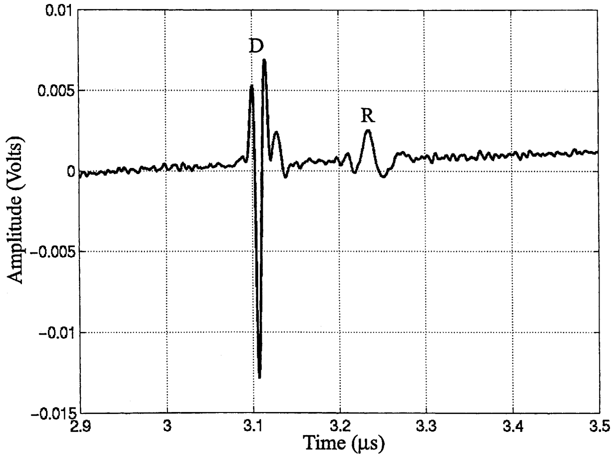

Fig. 7. Obtained time-resolved waveform from a thick glass specimen at $z = 0.75$ mm. D is the direct reflection arrival; R is the SAW arrival.

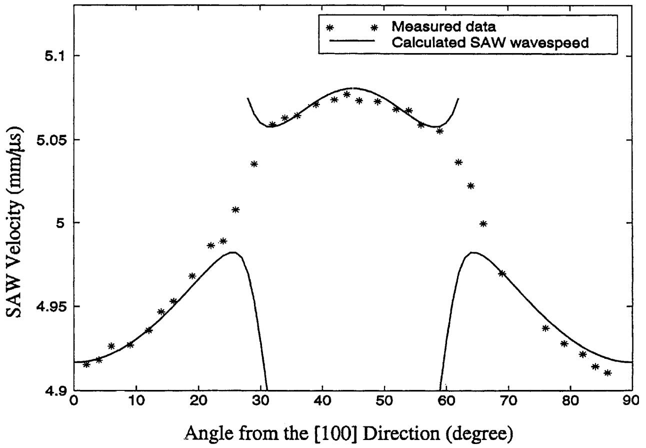

Fig. 8. Directional variation of SAW velocities on the (0 0 1) plane of cubic silicon.

this, SAW velocities were measured along various directions lying between the [1 0 0] and the [0 1 0] directions in a (0 0 1)-oriented cubic silicon wafer. The wavespeed measurements are shown with asterisk marks in the figure. Also shown for comparison are the calculated wavespeeds of the SAW and pseudo-SAW (PSAW) branches of (0 0 1) silicon. These were calculated using the elastic constants of silicon $C_{11} = 165.7$ GPa, $C_{12} = 63.9$ GPa, $C_{44} = 79.56$ GPa, and the density $\rho = 2332$ kg/m^3 [11]. In the angular range of 30° from the [1 0 0] direction the SAW in the (0 0 1) silicon crystal is almost sagittally polarized and so can be detected by the PVDF transducer. For directions lying between 30° and 60° from the [1 0 0] direction, the SAW is almost shear-horizontally (SH) polarized and therefore cannot be detected by the water-coupled PVDF transducer. Instead, the pseudo-SAW, which is sagittally polarized, is detected.

6. Conclusion

The design, construction, operating characteristics, and two applications of a line-focus transducer made of a 9 μm thick piezoelectric PVDF polymer film have been presented in this paper. Unique to this transducer is a PVDF backing behind active piezoelectric transducer film. The result is a transducer that possesses a wide frequency operating range which extends from 10 MHz to over 150 MHz. It is demonstrated that the transducer can be operated under either in a time-resolved pulse mode or in rf burst mode. An example of leaky SAW velocity measurements made in an anisotropic material, (0 0 1) silicon, has been shown.

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