Phase insensitive detection of laser-generated ultrasound

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An acoustic source formed by pulsed laser irradiation has been used to investigate the piezoelectric and acoustoelectric effects within a cadmium sulphide detector. Analysis of detected waveforms has enabled the two effects to be identified. The resulting transducer combination has application to imaging systems, where phase insensitivity may be required.

In many applications of ultrasound, such as medical imaging and nondestructive testing, the detected signal is complicated by phase distortion within the material under investigation, causing complicated interference processes. This problem may be overcome if the detector is phase insensitive, which in practice means the use of a small detector diameter or, if more sensitivity is required, a transducer which is itself phase insensitive. The latter approach makes use of the acoustoelectric effect within piezoelectric semiconducting materials (e.g., CdS, ZnO, and CdSe), where an interaction occurs between phonons and electrons.[1] Here, an ultrasonic wave within the acoustoelectric material generates electric potential variations, in which free carriers become trapped; hence, as the elastic wave propagates, an electric signal appears across the electrodes, whose magnitude is proportional to the incident ultrasonic energy.[2,3] This effect is not sensitive to the relative phases between multiple arrivals at the detector. In addition to this acoustoelectric signal, a piezoelectric signal will be generated as the wave enters the detector, and also when it reflects off a free surface. Due to the acoustoelectric effect, ultrasonic waves within the detector experience an attenuation above that normally expected from piezoelectric action only.

The basic operation of the acoustoelectric transducer can be understood from the following theoretical relations. As an ultrasonic wave propagates through a piezoelectric semiconductor, the electron-phonon interaction causes a local electric field E_{AE} to be generated which gives rise to an electric current density j given by[2,3]

$$j = \sigma E_{AE} = \frac{\mu}{v} \alpha \Phi. \tag{1}$$

Here μ is the electronic mobility, v the ultrasonic velocity, α the ultrasonic attenuation that results from the coupling of the ultrasonic wave to the mobile electrons, and Φ is the ultrasonic energy flux.[4] This equation shows that the acoustoelectric signal, which can be measured experimentally either as a dc current if the transducer is short circuited, or as a voltage $V_{AE} = E_{AE}\,dx$ if an open-circuited configuration is used, depends on the acoustic intensity and is therefore insensitive to phase variations caused by wave front distortion of the ultrasonic wave. The ultrasonic attenuation in (1) due to the electron-phonon interaction can be written[1]

$$\alpha = \frac{K^2}{v} \frac{\omega^2 \tau_c}{1 + \omega^2 \tau_c^2}, \tag{2}$$

where K^2 is the electromechanical coupling constant, ω the ultrasonic frequency, and $\tau_c = \epsilon\epsilon_0/\sigma$ the conductivity relaxation time, ϵ and σ being the dielectric permittivity and the electrical conductivity, respectively. (This expression assumes that the diffusion relaxation time τ_D is sufficiently short that it can be neglected, an assumption that is valid for the results discussed below.[2]) Through its dependence on τ_c, the attenuation varies strongly with the conductivity, being a maximum for values of ω and σ such that $\omega\tau_c = 1$. From (1) it is clear that a large attenuation is desirable for efficient operation of the acoustoelectric transducer.

In this letter, the properties of CdS as a phase insensitive detector will be investigated, using an acoustic source formed by pulsed laser irradiation. CdS was chosen as the detector, since its conductivity can be varied over many orders of magnitude by optical illumination, so that acoustoelectric sensitivity can be optimized. The laser source has been well characterized in the past by various workers,[5,6] and has been suggested for use as a standard acoustic source.[7] In this case, it was used because of its wide bandwidth and reproducibility. Several mechanisms for elastic wave generation are possible using the pulsed laser. The first relies on thermal expansion of the irradiated surface, following the absorption of laser energy, and results in a source characterized by dipolar horizontal stresses with a steplike time dependence. A second source may be formed by the evaporation of a liquid coating, resulting in a pulsed normal force. Finally, irradiation through a solid layer, attached rigidly to the surface, may result in an acoustic resonance within the coating leading to a damped oscillatory normal force.

To investigate the displacement waveforms generated by such sources, and to demonstrate the piezoelectric response expected within thick detectors, a 19-mm-long, 10-mm-diam lead zirconate titanate (PZT) piezoelectric ceramic detector was first used as shown in Fig. 1. Generation within a 14-mm-thick aluminum sample was achieved using single 30-ns laser pulses from a Q-switched, frequency-doubled ruby laser, operating at 347 nm in the ultraviolet. It was reflected onto one face of the sample via mirrors with the PZT directly opposite it on the other face. PZT signals were amplified, and subsequently digitized using a Data Precision Data 6000 waveform recorder.

Figure 2 shows the waveforms recorded following generation by (a) evaporation of a thin liquid (oil) layer, (b) irradiation through an attached 0.1-mm-thick polymer tape, and (c) thermal expansion only. In each case, several signals may be identified, as shown on each waveform. The direct longitudinal (p) and shear (s) arrivals were evident as separate signals. The multiply reflected longitudinal signal with-

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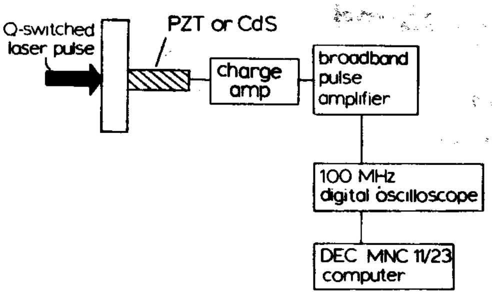

FIG. 1. Schematic diagram of apparatus.

in the aluminum sample ($3p$) arrived at a similar time to that taken for the longitudinal wave to propagate to the back of the detector and produce a signal (p'); hence, the two signals were combined on the waveform. Note that the longitudinal wave produces a piezoelectric signal only at the electroded faces of the PZT, it being inverted at the back face with respect to that formed at the face coupled to the sample. Note also the interesting features of the direct (p) and (s) arrivals. The thermoelastic source [Fig. 2(c)] results in a large shear displacement, whereas the other two sources lead to prominent longitudinal signals. In the liquid evaporation source, this was dipolar in nature, whereas it was oscillatory for the polymer layer source, as expected from the discussion above.

The thick PZT detector was now replaced by the CdS single crystal, of 21 mm thickness and 6 mm × 7 mm cross section, with its c axis perpendicular to its front face. Hence, this arrangement would make the CdS sensitive to longitudinal waves traveling along the crystal axis, with sensitivity to shear waves being confined to off-axis propagation. It was illuminated uniformly from the two sides by light from Hg arc lamps and a suitable lens system. The above experiments were then repeated for each of the laser generated acoustic sources, using the CdS detector under illuminated and dark conditions. In the former case, both piezoelectric and acoustoelectric responses were expected, whereas pieozelectric action only would be present in the latter arrangement.

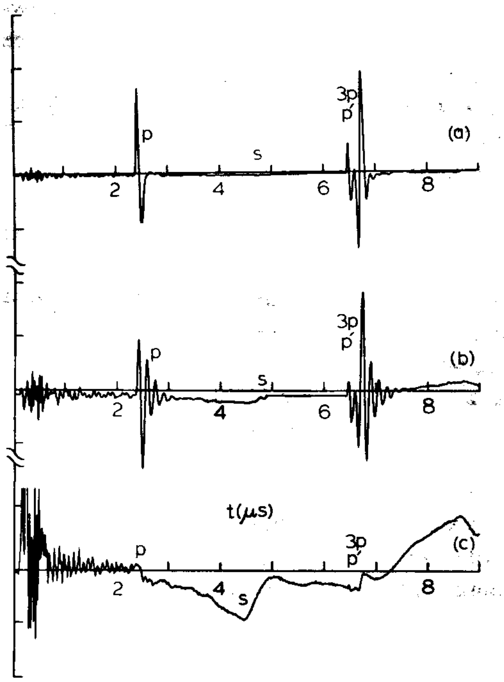

FIG. 2. Waveforms generated by pulsed laser irradiation following detection by a thick PZT transducer. Contributions to the waveforms are as follows: p and s, direct longitudinal and shear waves respectively; $3p$, longitudinal wave multiply reflected in aluminum sample; p', longitudinal wave reflecting from back surface of detector. (a) Generation in the presence of a thin oil layer; (b) surface treated with a 0.1-mm-thick polymer coating; (c) thermoelastic generation at an untreated surface, vertical scale × 10 with respect to (a) and (b).

Consider first the oil evaporation source in Fig. 3. In the absence of illumination, Fig. 3(a), the waveform was similar to that detected using the thick PZT detector [Fig. 2(a)] although now the $3p$ and p' signals were observed as separate transients. Note, in addition, the large p' signal in comparison to that produced at the detectors front face (p). This was thought to be due to the high damping of front face vibrations, due to bonding of the detector to the aluminum sample. The longitudinal acoustic velocity in the CdS sample was determined from the transit time between the p and p' signals, and was estimated to be 4.460 ms $\pm$ 10 ms^{-1}. This value is in good agreement with other measurements in CdS under similar conditions[8]; note that the acoustic velocity changes slightly[1,2] (by up to about 1%) as the optical illumination is varied, this change in velocity being the Kramers–Kronig equivalent of Eq. (2) for the attenuation.

The waveform of Fig. 3(a) represented the purely piezoelectric response; however, with the detector under optical illumination, a large acoustoelectric effect is superimposed, as shown in Fig. 3(b). In this case, a marked decrease in the p' signal amplitude was observed, due to increased attenuation of the longitudinal wave within the CdS as predicted by Eq. (2). This energy was used to provide the acoustoelectric effect, resulting in an increased low-frequency signal from p and s wave propagation within the detector. This is consistent with the predictions of Eq. (1), i.e., that a large attenuation in the detector gives rise to an enhanced

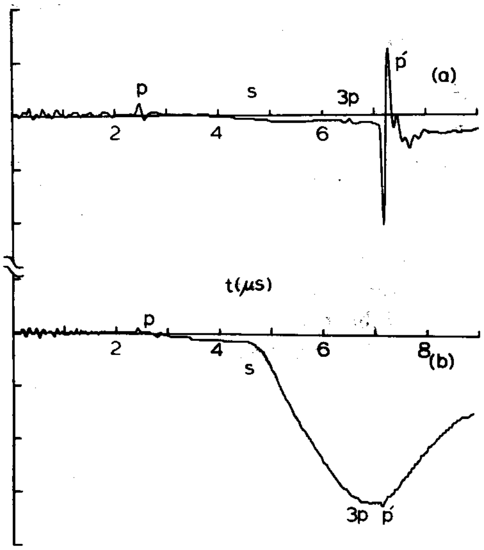

FIG. 3. Waveforms detected by CdS transducer, following generation by an oil evaporation source. (a) No illumination, piezoelectric response only; (b) UV illumination, superposition of acoustoelectric response, vertical scale divided by 10 with respect to (a). Piezoelectric responses annotated as Fig. 2. Vertical scale arbitrary in both.

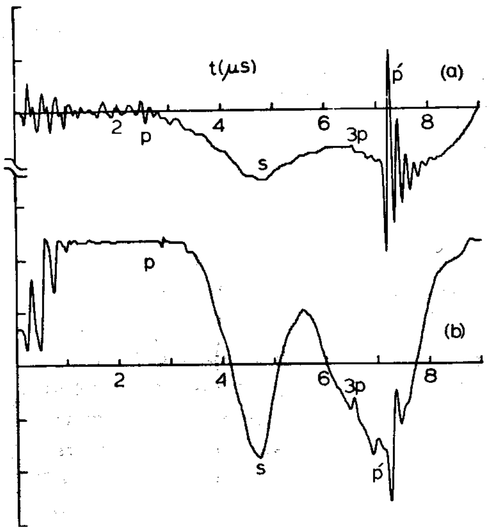

FIG. 4. As Fig. 3, generation through a 0.1-mm-thick polymer coating.

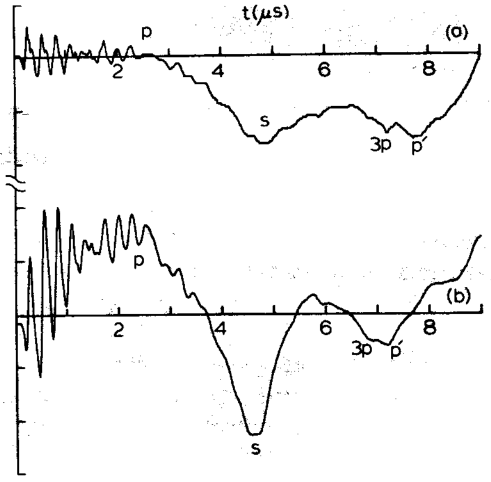

FIG. 5. As Fig. 3, thermoelastic generation at a clean surface. Vertical scales equal in (a) and (b).

acoustoelectric signal. The slope of the acoustoelectric signal changed sign at the p' arrival, since the reflected signal, traveling in the opposite direction, caused a change in sign of the acoustoelectric contribution.

Similar trends were observed for the source generated by irradiation through the 0.1-mm-thick polymer layer, as shown in Fig. 4. The piezoelectric signal, Fig. 4(a), exhibited the expected oscillatory longitudinal signals. The acoustoelectric response again dominated the p' signal as shown in Fig. 4 (b). Note, however, that in Fig. 4(b) the slope of the signal changed sign at the expected time of arrival at the detector of the shear wave (s), a phenomenon that merits further investigation. The thermoelastic source, Fig. 5, also demonstrated that optical illumination of the CdS gave rise to an enhanced low-frequency signal, which again changed sign at the shear arrival.

It is clear from the above that piezoelectric and acoustoelectric signals detected by the CdS were readily distinguishable, and in fact the piezoelectric response is easily filtered out, being of a higher frequency content. Thus, phase insensitive experiments may be conducted, using a noncontact, wide bandwidth laser source and the illuminated CdS detector. In our experiments, this was bonded rigidly to the sample; however, when used with a water couplant, the result would be a useful tool in many imaging experiments requiring phase insensitivity.

An interesting point is that the authors observed some acoustoelectric action when the illumination from the arc lamps was absent. This was due to illumination of the CdS by scattered laser energy from the Q-switched laser, which operated in the UV. Thus, with suitable geometrical arrangement, it may be possible to use the CdS with the laser generator as a phase insensitive system without the need for a separate and inconvenient illumination setup.

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