Acoustoelectric Harmonic Generation in a Photoconductive Piezoelectric Semiconductor

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Abstract. Piezoelectric semiconductors can exhibit harmonic generation because of nonlinear interactions between the acoustic and electric fields in the solid. To observe this effect, longitudinal waves were excited in crystalline cadmium sulfide. Because CdS is highly photosensitive, its conductivity can be changed by several orders of magnitude by varying the applied light level. The velocity and attenuation at 4.1 MHz and 8.2 MHz were measured and shown to be strong functions of conductivity in the range 0.001-0.010 $\Omega^{-1}m^{-1}$. Fitting the resulting data with linearized theory yielded values for the piezoelectric stress and elastic moduli that were consistent with literature values. Also, harmonic generation resulting from excitation at 4.1 MHz was measured. The amplitudes of the second to fifth harmonics exhibited oscillatory behavior as a function of conductivity, particularly in the aforementioned range. Finally, the second harmonic amplitude was also measured at multiple propagation distances, and the conductivity of its peak amplitude was shown to shift to lower conductivity at further distances.

Keywords: Acoustoelectric effect, Harmonic generation, Piezoelectric semiconductor, Photoconductivity, Cadmium sulfide
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INTRODUCTION

When appropriately polarized acoustic waves propagate in specific directions in piezoelectric semiconductors, the modulated electric field induced by the wave causes conduction electrons to bunch together. This *acoustoelectric effect* involves nonlinear coupling of the electric field and charge density, which results in an internal dc electric field as well as higher electric and acoustic harmonics. Most of the theoretical and experimental work in nonlinear acoustics on this topic has been limited to second harmonic generation [1–3] or parametric interactions [4,5] or has included the effects of an applied external electric field [1–6]. The latter can give rise to amplification and other effects, as has been described in several reviews [7–9] and tends to result in exponential growth of certain modes over all others.

In this paper, we describe experiments on the generation of higher harmonics in the low frequency regime ($\omega\tau \ll 1$, where ω is angular frequency and τ is the electronic relaxation time) and without application of an external electric field. Longitudinal bulk waves were excited along the hexagonal axis of undoped cadmium sulfide, a direction that was chosen because of its high piezoelectric activity.

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THEORY

It can be shown that the propagation of longitudinal bulk waves in a piezoelectric semiconductor in one dimension can be described by [3]:

$$\frac{\partial^2 T}{\partial z^2} - \frac{\rho_m}{c^D}\frac{\partial^2 T}{\partial t^2} - \frac{\rho_m}{c^D}\kappa\sqrt{\frac{c}{\varepsilon}}\frac{\partial^2 D}{\partial t^2} = 0\,, \tag{1}$$

$$\frac{\partial D}{\partial t} + \frac{\mu q n_0}{\varepsilon^T}\left(D - \sqrt{\frac{\varepsilon}{c}}\kappa T\right) - D_n\frac{\partial^2 D}{\partial z^2} = \frac{\mu}{\varepsilon^T}\left(D - \sqrt{\frac{\varepsilon}{c}}\kappa T\right)\frac{\partial D}{\partial z}\,, \tag{2}$$

where z is distance, t is time, T is stress, ρ_m is mass density, $c^D = c(1+\kappa^2)$, c is stiffness modulus, $\kappa^2 = e^2/c\varepsilon$, e is piezoelectric modulus, ε is dielectric permittivity, D is electric displacement, μ is mobility, q is magnitude of electric charge, n_0 is equilibrium electron number density, $\varepsilon^T = \varepsilon(1+\kappa^2)$, and D_n is diffusion coefficient. In a quasilinear solution with fundamental $T_1(z=0) = T_1^0\exp(i\omega t - q_1 z)$ and second harmonic $T_2(z=0)=0$, it was shown that the second harmonic of the acoustic stress has the form

$$T_2 = \frac{F}{q_2 - 2q_1}\left(e^{-i2q_1 z} - e^{-iq_2 z}\right)e^{i2\omega t}\,, \tag{3}$$

where q_j is wavenumber of the jth harmonic and F is given in [3]. Qualitatively, the amplitude of the second harmonic exhibits oscillations as a function of conductivity, and the nature of these oscillations evolves as a function of distance [2–5]. However, experimental data corroborating this result are limited [2,4] and higher harmonics do not appear to have been measured.

EXPERIMENT

Figure 1 shows the experimental apparatus. The CdS crystal was placed in a temperature-controlled bath, and acoustic transducers were placed on opposite faces. The conductivity of the crystal was varied by changing the illumination using an Interlux DC1100 digitally-controlled light source with dc power to enhance its stability. A photometer was utilized to monitor and ensure consistent illumination. To generate, receive, and process the acoustic signal, a Ritec SNAP-1-30 system was employed along with a LeCroy LT342L Digital Oscilloscope. For the velocity and

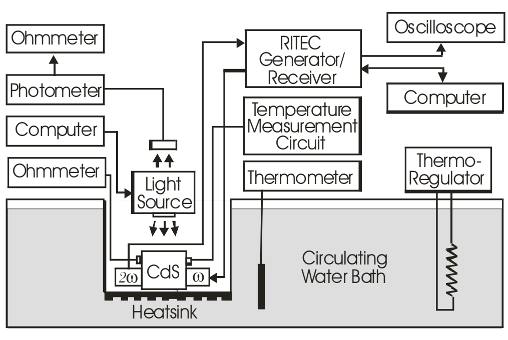

FIGURE 1. Experimental apparatus.

attenuation measurements, 8 cycle, 4.1 MHz and 8.2 MHz signals were generated with 3.5 MHz and 7.5 MHz Xactex transducers, respectively, each operating in reflection mode. For measurement of the harmonics, a transmission setup was used with the fundamental of 4.1 MHz generated with the 3.5 MHz Xactex transducer, the second harmonic detected with a 7.5 MHz Aerotech transducer, and higher harmonics detected with a 15 MHz Aerotech transducer. A 5 MHz low-pass filter assured that no higher harmonics entered the crystal, while a 5 MHz high-pass filter eliminated the fundamental frequency from entering the Ritec system. The amplitudes of the higher harmonics were measured relative to the second harmonic and were appropriately scaled with respect to the sensitivity of the 15 MHz transducer.

RESULTS AND DISCUSSION

Figure 2 shows the resulting velocity and attenuation measurements as a function of conductivity, along with theoretical curves [10] fitted by setting c = 88.7 GPa, e = 0.515 C/m^2, and the light penetration depth d_p=140 μm, the latter quantity used to compute the conductivity from resistance measurements. These values are consistent with those reported by Hudson and White [10] and Bube [11]. In addition, a constant was added to the attenuation to account for attenuation that was not a result of the acoustoelectric effect. The velocity and attenuation are not independent, and compromises were made in the fitting to favor the velocity data, which were deemed more accurate. The reasons for the significant underestimation of the attenuation at 8.2 MHz are not entirely clear but may be at least partially attributed to the generation of higher harmonics, which is not accounted for in the linear theory of Ref. 10.

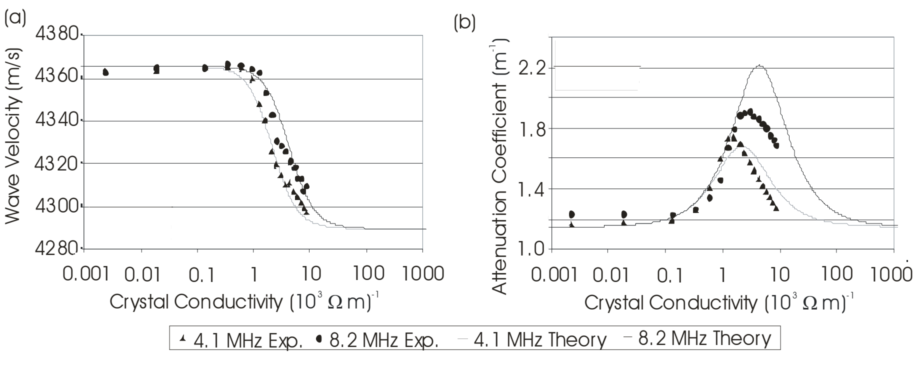

FIGURE 2. (a) Velocity and (b) attenuation of the fundamental frequencies 4.1 MHz and 8.2 MHz as a function of crystal conductivity.

Figure 3(a) shows amplitude of the second harmonic at 8.2 MHz as a function of conductivity. The successive curves show the first received pulse of the second harmonic as well as three consecutive echoes. As can be seen, the amplitude of the first pulse passes through a maximum around 0.009 Ω^{-1} m^{-1}, but the maxima of subsequent echoes shifts to lower conductivities as the pulse travels further. Initial theoretical calculations which account for only the second harmonic [Eq. (3)] appear to qualitatively correspond with these observations, Figure 3(b) shows the second (8.2 MHz), third (12.3 MHz), fourth (16.4 MHz), and fifth (20.5 MHz) harmonics as a function of conductivity. The second harmonic has a minimum near 0.009 Ω^{-1} m^{-1}, while the other harmonics have multiple minima in the range 0.005–0.009 Ω^{-1} m^{-1}.

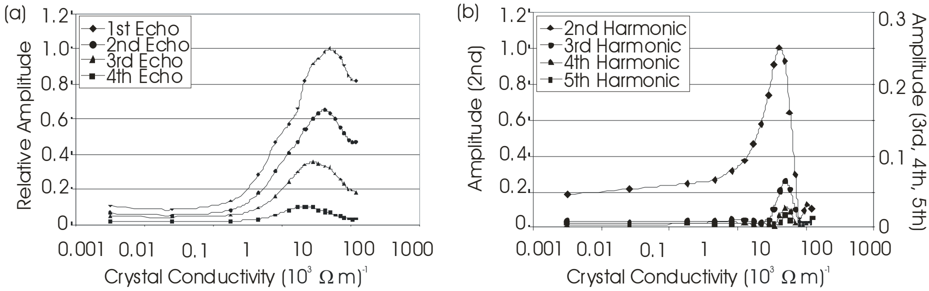

FIGURE 3. Relative amplitudes of (a) consecutive echoes of the second harmonic and (b) amplitudes of the second to fifth harmonics of a 4.1 MHz fundamental.

CONCLUSION

Measurements of the velocity of longitudinal bulk waves along the hexagonal axis of CdS have been shown to be consistent with known linearized theory. The amplitudes of the second through fifth harmonics of a 4.1 MHz fundamental have been measured and show oscillations of the sort predicted by quasilinear theory for the second harmonic component.

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