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ECHO PROPERTIES OF BGO AND CdS

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Abstract.—A brief discussion is given of the theory of echo generation in insulators and semiconductors. For semiconductors it is shown that $\omega, 2\omega$ echo generation may occur without dc-field present. In this case the echo amplitude is directly proportional to the electronic conductivity and the applied fields. Experiments in CdS support the predictions. From measurements on BGO it is concluded that interactions with vacancies which is responsible for strong acoustic attenuation at low temperatures, does not contribute in the echo generation.

1. Introduction.—Wavevector reversed phonon echoes have recently been used as a powerful tool in studying phase transitions\(^1,2\). The present work is aimed at a further mapping of echo properties of single crystals in order to find proper materials for such use. In addition it is of great interest to attain an improved understanding of the origin of the echo mechanism itself. For a more general discussion of phonon echoes we refer to a forthcoming review\(^3\).

2. Theory.—Starting from a free energy expansion in strain $S$ and electric field $E$, and applying Poisson's equation, Newton's 2nd law (in one dimension) can be written:

$$\rho \frac{\partial^2 u}{\partial t^2} - c_o \frac{\partial^2 u}{\partial z^2} = c_1 ES + c_2 E^2 S + \frac{eQ}{\varepsilon} n_S (1 + \kappa E + \ldots) + \ldots$$  \hspace{1cm} (1)

where $u$ is the mechanical displacement, $\rho$ is the mass density, $c_o$ is the piezoelectrically stiffened elastical constant, $c_1$, $c_2$ and $\kappa$ are functions of various electroacoustic coupling constants, $e$ is the piezoelectric constant, $Q$ is the elementary charge, $\varepsilon$ the dielectric constant and $n_S$ denotes the space charge density.

In insulating dielectrics $n_S = 0$. A term associated with an electroacoustic nonlinearity $c_n$ in this case gives rise to an $\omega, 2\omega/n$ echo ($n$ is an integer). This means that a forward propagating strain wave of frequency $\omega$, $S_F - S_O \cos(\omega t - k z)$ is mixed with an electric field of frequency $2\omega/n$ i.e. $E^R - E_O^R \cos \frac{2\omega}{n} t$, to produce a backward wave echo

$$S_B - S_O E_O^R \sin(\omega t + k z)$$  \hspace{1cm} (2)
In centrosymmetric crystals all odd numbered constants $c_{2n+1}$ vanish, so the lowest order echo will be an $\omega,\omega$ echo. Otherwise, $\omega,2\omega$ echoes are of lowest order.

In semiconductors $n_s \neq 0$. In addition to the mechanism discussed above, the last terms in (1) now provide sources for echo generation. As explained by Melcher and Shiren, $n_s$ will contain a backward wave component if the applied strain and field have the same frequency ($\omega,\omega$). They found that $\omega,\omega$ echoes as well as $\omega,\omega/n$ echoes may originate from the term $\frac{e\sigma_0}{\epsilon}n_s$ in (1). This term can not give rise to for instance $\omega,2\omega$ echoes except with application of a dc-field. We find, however, that unbiased $\omega,2\omega$ echo generation may occur from the term $\frac{e\sigma_0}{\epsilon}n_s x E$. From the equation of charge continuity and the expression for the current density, $n_s$ is found to contain a term proportional to $\sigma_0 x E \cos(\omega t - k z)$. $\sigma_0$ is the static electronic conductivity. Mixing $n_s$ with $E$, a backward echo is formed:

$$S_b = \sigma_0 E \sin(\omega t + k z).$$

(3)

$\sigma_0$ generally depends on illumination, temperature and possibly on field amplitudes $S_o$ and $E_o$, as well as pulse widths and repetition rate.

When $n_s = 0$, storage echo phenomena may also occur.

3. **Echoes in BGO (Bi$_{12}$GeO$_{20}$).** In the present work, $\omega,2\omega$ echoes have been observed in BGO with several modes of sound propagation in broad ranges of frequency and temperature.

The echo amplitude dependence on strain and electric field has proved to be bilinear, as expected from Eq.(2). No saturation effects are seen.

With pulsed fields the resulting echo is shown experimentally to be the convolved product of the input pulses, with the time scaled by a factor two for the second (E) pulse.

![Fig. 1: Echo and attenuation vs. temperature in BGO. From Ref. 3.](image-url)
Fig. 2: $\omega, 2\omega$ echo amplitude in CdS at room temperature versus electronic conductivity for various $2\omega$ fields. The fully drawn lines are predicted from Eq. (3).

The temperature dependence of the echo at 100 MHz is given in Fig. 1. The reduction in measured echo amplitude near 55 K is completely attributed to the increased absorption in this temperature region. Hence vacancy diffusion in the Ge sublattice, which is responsible for the attenuation peak, does not have any influence on the formation of phonon echoes.

4. Echoes in CdS. - Measurements are performed with 4 different CdS-crystals of high dark resistivity ($10^8 - 10^{10} \Omega \text{cm}$), supplied from 3 different sources. All these crystals show strong unbiased $\omega, 2\omega$ echoes, and also $\omega, \omega$ echoes at room temperature.

The $\omega, 2\omega$ echo amplitude is found to be proportional to the electronic conductivity, in agreement with the prediction in Eq. (3). This is illustrated in Fig. 2, where the conductivity is changed by continuously varying the voltage of a white light lamp. The relative change in conductivity, $\Delta \sigma$, is measured by detecting the change in ultrasonic attenuation, $\Delta \alpha$. In all our CdS-crystals, the attenuation increases with increasing conductivity. Theory predicts:

$$\Delta \alpha = \frac{K^2}{2\varepsilon_s v_s} \Delta \sigma$$

(4)

where $K^2$ is the electromechanical coupling constant and $v_s$ is the sound velocity. The deviation from the predicted line for maximum field (0 dB) is due to field-dependent photoconductivity for this crystal.

For two of the crystals the photoconductivity and accordingly the echo amplitude is seen to depend nonlinearly on excitation field amplitudes and pulse widths as well as the rf-repetition rate.

References.