small or large modulation amplitude. The apparent saturation of the relative harmonic strengths [Fig. 3(b)] below the value predicted for the hysteresis model is consistent instead with a smooth transition through the multiple-valued region.

Having shown that the oscillations at the antinode are strongly affected by magnetic interaction using a single-frequency analysis, we turn again to beats and the production of a difference frequency. Employing the approach of Eq. (1) with slightly modified symbols, we have

$$\eta = \alpha_1 \sin f_1(\rho - \eta) + \alpha_2 \sin f_2(\rho - \eta), \qquad (2)$$

where $\eta = 8\pi^2 I_{\mathrm{tot}}/H^2$, $\alpha_1 = 8\pi^2 I_{01}/H^2$, $\rho = 2\pi/H$, etc. Analytic solution is possible in the low-a limit, showing, in addition to the single-frequency results described above, the generation of all mixing products. Among these is a difference frequency with amplitude comparable to that of the single-component third harmonic. The numerical solution necessary to compare amplitudes of carrier and f_D for large a have not yet been carried out, although the nearly equal values obtained for the magnetization amplitudes are consistent with a strong sensitivity to large a. In summary, the evidence that the beat in the cigar frequencies generates f_D (and not vice versa) is (1) strong beats persist to low magnetic fields and high temperatures where f_D is unobservable, and (2) the carrier shows a large a value through an entire beat.

On the basis of Eq. (1), the influence of sample shape should be simply accounted for by the use of a demagnetizing factor introduced as a multiplier of y in the argument. Thus, the disk ought to exhibit very little magnetic interaction or, equivalently, low a values. Compared to the rod, the disk does show lower a values, but there was still a tendency to saturate in the temperature dependence of the fundamental, a generation of f_D at a lower amplitude compared to the rod, and an unusual behavior of the Fourier components characterized by the second harmonic dropping out, particularly in the antinodes, to yield a triangular wave form for the magnetization.[6] This seems to imply that the direct introduction of demagnetizing factors is inadequate to account for the effects of sample shape.

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[2]A. B. Pippard, Proc. Roy. Soc. (London) A272, 192 (1963).

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[4]Distilled, zone-refined material prepared by Nuclear Metals, Inc., and supplied to us through the U. S. Air Force Office of Scientific Research and the U. S. Atomic Energy Commission. The rod was spark-machined for us by Nuclear Metals, Inc., and the disk by M. Herman of the Franklin Institute. Both specimens exhibit <1° spread in microstructure.

[5]B. R. Watts, Phys. Letters 3, 284 (1963).

[6]J. H. Condon (private communication) has checked these measurements on different rod- and disk-shaped samples using a torsion method and observes similar effects.

TRANSIENT ACOUSTOELECTRIC SATURATION EFFECTS IN ZnS AND CdS CRYSTALS

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Since the discovery of ultrasonic amplification in CdS[1] considerable interest has been shown in the interaction of the drifting electrons with the piezoelectric lattice modes. The work of Smith[2] and McFee[3] showed that this interaction leads to pronounced saturation effects in the current-voltage characteristics of CdS. The results indicated that in most cases saturation sets in when the electron drift velocity v_d just exceeds the velocity of sound in the crystal. In these experiments, specimen conductivities above about $10^{-5}\ \Omega^{-1}\ \mathrm{cm}^{-1}$ were necessary and the measurements were carried out on semiconducting or on highly photoconductive specimens under strong uniform illumination. McFee's results showed that with $\sigma \sim 10^{-5}\ \Omega^{-1}\ \mathrm{cm}^{-1}$, the build-up of the ultrasonic flux to its saturation value required a considerable number of sonic tran-

sits, and in his particular case current saturation set in about 80 μsec after application of the field pulse. According to the theory of White,[4] the ultrasonic gain per unit length increases with increasing σ and, as expected, the onset of current saturation in Smith's semiconducting specimens ($\sigma > 10^{-2}\ \Omega^{-1}\ \mathrm{cm}^{-1}$) occurred far more rapidly.

In this note we wish to report an essentially different, and perhaps more direct, experimental approach to the study of acoustoelectric interaction which is shown to be applicable also to highly resistive piezoelectric materials. From the investigation of single transits of generated carriers it appears that under these experimental conditions, and with specimen conductivities as low as $10^{-11}\ \Omega^{-1}\ \mathrm{cm}^{-1}$, the buildup of a sufficient level of ultrasonic flux for strong local interaction with the carriers takes place within a fraction of the transit time.

The experiments were carried out on thin, highly resistive platelet crystals of hexagonal and cubic ZnS and of CdS. They measured a few mm in side length and ranged in thickness from 100 to 1400 μ. Opposite platelet faces were fitted with evaporated electrodes, generally Au (top) and In (bottom). Unlike the previous work, in which the carrier density was essentially constant throughout the specimen volume, the present experiments were carried out under highly nonuniform pulse excitation. Free carriers were generated in a narrow layer (about 5 μ deep) below the top electrode by a fast electron pulse of 5 to 30 nsec duration.[5] Alternatively, in the case of some of the CdS specimens, excitation by a strongly absorbed light flash was used. About 1 msec before the excitation pulse a field was applied across the crystal for several msec. The experiment could be run either at single-shot operation or at a repetition rate of 50 pps. As in previously described drift mobility experiments on insulating solids,[6] the charge displacement of the drifting sheet of generated electrons was integrated and displayed on wide-band electronic equipment. The transit time t_t could be measured directly and from the known specimen thickness d, the drift velocity $v_d = d/t_t$ was obtained. For ZnS and most of the CdS crystals, a gold top electrode was found to be sufficiently blocking to prevent any appreciable injection of additional carriers after the excitation pulse.

Figures 1(a) and 1(b) show a number of typical curves illustrating the field dependence of

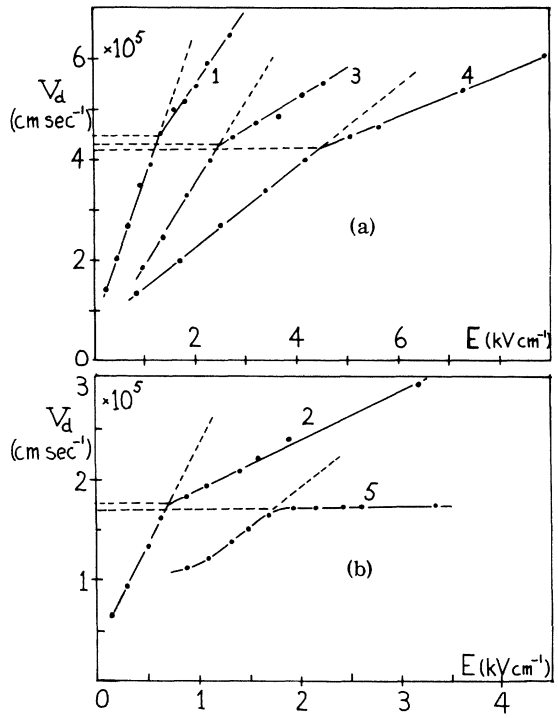

FIG. 1. Measured drift velocity v_d as a function of the applied field E for CdS and ZnS crystals. The curves are numbered to correspond to the data in Table I.

the measured drift velocity, both along and perpendicular to the c axis for the hexagonal specimens and along the [111] direction for the cubic ZnS crystals. At the lower E values, the gradient of the straight portion leads to a value for the electron drift mobility μ_e.[7] A sharply defined change in slope takes place at a critical velocity v_d', and at higher fields the slope is about half its original value, as predicted by Prohofsky,[8] although a more complete saturation (e.g., curve 5) is occasionally observed. It was found that both single-shot and 50-pps excitation gave the same results.

The data referring to the crystals in Fig. 1 are listed in Table I. Similar experiments on 10 other CdS and ZnS specimens led to v_d' values in good agreement with those given. In addition, the current pulse height has been investigated as a function of E on most of the above specimens. The change in gradient of the curves at a critical field E' was normally found to be as sharp as in those shown in Fig. 1. However, in some cases longer excitation pulses (up to 300 nsec) were needed. Values of $\mu E'$ are given in Table I. The last column lists the independently deter-

Table I. Summary of specimen data and of results from Fig. 1. Electron mobility μ_e and critical velocity v_d' from drift mobility experiments; $\mu E'$, critical velocity from current saturation experiments; v_s, velocity of sound from elastic or ultrasonic measurements.[a,b]

Curve (Fig. 1)	Specimen	Direction of electron flow	d (μ)	μ_e ($cm^2\ V^{-1}\ sec^{-1}$)	v_d' (10^5 cm sec^{-1})	$\mu E'$ (10^5 cm sec^{-1})	v_s (10^5 cm sec^{-1})
1	CdS	$\parallel c$ axis	450	280	4.4	4.3	4.41[a]
2	CdS	$\perp c$ axis	1400	187	1.8	1.7	1.76[a]
3	ZnS (cubic)	$\parallel$ [111]	211	165	4.3	4.5	5.8, (3.4)[b]
4	ZnS (cubic)	$\parallel$ [111]	536	79	4.2	4.4	5.8, (3.4)[b]
5	ZnS (hexagonal)	$\perp c$ axis	135	80	1.7	1.8	...

[a]D. I. Bolef, N. T. Melamed, and M. Menes, J. Phys. Chem. Solids 17, 143 (1960).

[b]The value of v_s along [111] as calculated from elastic constants by D. Berlincourt, H. Jaffe, and L. R. Shiozawa, Phys. Rev. 129, 1009 (1963), is 5.8×10^5 cm sec^{-1}. The discrepancy between this and our experimental values may possibly arise from interactions with piezoelectrically active shear waves along [110] and equivalent directions, for which the velocity is 3.4×10^5 cm sec^{-1}.

mined value of the appropriate velocity of sound obtained or calculated from the quoted references.

The close agreement of v_d', $\mu E'$, and v_s for CdS shows convincingly that the observed effects are associated with an interaction of the drifting electrons and the piezoelectric modes. The results show a clear distinction between longitudinal- and shear-wave interaction in the CdS specimens. None of the difficulties reported by McFee[3] in the case of longitudinal wave specimens was experienced in the present experiments. A number of the crystals investigated gave drift mobility values lying well below the lattice mobility. In these cases t_t included the total time the electrons spend in shallow trapping centers during transit. This, however, did not seem to affect the determined values of v_d' and $\mu E'$.

The main difficulty consists in explaining the rapid buildup of the ultrasonic flux in specimens having dark conductivities between 10^{-10} and $10^{-11}\ \Omega^{-1}\ cm^{-1}$. After excitation, the effective conductivity in the drifting sheet of electrons is only about $10^{-7}\ \Omega^{-1}\ cm^{-1}$. From the rising edge of the observed transit signal at $v_d > v_d'$, it is estimated that the electrons reach the v_d values of Fig. 1 in less than 20 nsec after the end of the excitation pulse.

Clearly these results cannot be explained in terms of the linear amplification theory of White.[4] The possibility that a sufficient level of ultrasonic flux might be generated by the field pulse (applied about 1 msec before excitation) cannot be entirely excluded. However, this would seem unlikely in view of the low dark conductivities and of the slowly rising field pulses used in most of the experiments.[9] It is far more likely that the rapid flux buildup is associated with the nonuniform pulse excitation of the free carriers, and this possibility is being investigated at present.

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[6]W. E. Spear and J. Mort, Proc. Phys. Soc. (London) 81, 130 (1963); W. E. Spear, ibid. 76, 826 (1960).

[7]The leveling out of curve (5) at the lowest fields occurs because the transit time approaches the electron lifetime with respect to deeper trapping centers.[6]

[8]E. W. Prohofsky, Phys. Rev. 134, A1302 (1964).

[9]A pulse rise time of about 0.5 msec ensured the absence of shock excitation.