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XI-8. Acoustoelectric Effect in Semiconducting CdS

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Probe measurements of the field distribution along conducting CdS filaments under acoustic-gain conditions show that throughout its buildup the ultrasonic flux is highly concentrated: in propagating domains in the transient state and in a stationary domain bordering with the anode at steady state. Whereas the propagating domains are generated at the cathode (by shock excitation), the stationary domain consists of amplified ultrasonic noise originating near the anode and reinforced by reflections from the anode boundary.

§ 1. Introduction

The various results reported in the literature[1] on the current oscillations accompanying the buildup of acoustic flux in piezoelectric materials, the damping out of the oscillations with time, and the manner in which steady-state conditions are established are not always in accord and are sometimes even contradictory. Probe measurements of the internal field distribution resolve most of these difficulties and provide a clear and self-consistent picture of the acoustoelectric effect, at least in the case of semiconducting CdS. Such measurements reveal that throughout its buildup, the acoustic flux is highly concentrated: in propagating domains in the transient state and in a stationary domain bordering with the anode when the steady state is reached. Propagating flux domains have been observed in GaAs,[2,3] GaSb,[4] CdS[5~7] and Te,[8] but their exact relation to the attending current oscillations has not been established. The present measurements show that in every case the current oscillations can be *quantitatively* accounted for in terms of the time-varying nonohmic resistance associated with the propagating domains. The period and especially the decay time of the oscillations are controlled by small inhomogeneities in filament resistance so that unless probe techniques are employed work on samples of extreme uniformity is necessary if any value is to be attached to these parameters. Probe techniques have proved particularly useful in elucidating the processes leading to steady-state conditions.

§ 2. Results and Discussion

Transient conditions

The measurements were carried out on rectangular filaments oriented normal to the *c*-axis and ranging in resistivity between 2 and 10 ohm-cm. The field distribution along the filament was obtained by a pair of potential probes mounted on a movable frame. The pulsed drift field was applied either under constant-voltage conditions (series resistance R_s small compared to the filament resistance R_0) or under nearly constant-current conditions ($R_s \gg R_0$), the results being much the same in the two cases. Typical oscillograms obtained under intermediate conditions ($R_s = R_0$) are shown in Fig. 1 for a drift field exceeding the threshold for acoustic amplification. The oscillations in the voltage V_f across the entire filament (Fig. 1 a) reflect the

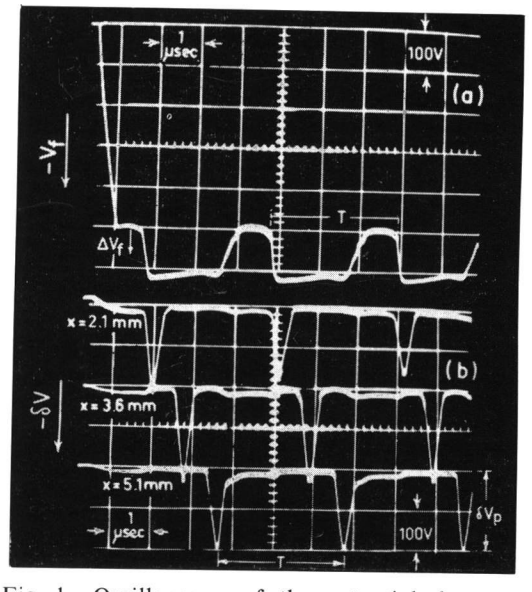

Fig. 1. Oscillograms of the potential drop (a) across entire filament and (b) across pair of probes (separation 0.25 mm) for three distances x of their center from the cathode. Filament length 5.5 mm, resistivity 7.2 ohm-cm; $R_s = R_0 = 560$ ohm.

variations in filament resistance between the ohmic value (R_0) and some higher value ($R_0+\Delta R_{max}$) attained when the acoustic flux in the sample builds up to its highest level. (R_0 and $R_0+\Delta R_{max}$ correspond, respectively, to the crests and troughs of the current oscillations commonly reported in the literature.) Fig. 1 b displays the potential drop δV across the probes for three distances x of their center from the cathode. In each trace δV is initially small but after a certain time interval, a narrow high-resistance domain of ultrasonic flux arrives between the probes and δV exhibits a sharp rise to its peak value δV_p. As the domain moves out, δV drops and assumes again its low ohmic value, until a second domain arrives and the process is repeated, either indefinitely or with decaying amplitude (see below). The mode of propagation of the domains is apparent from the displacements along the time axis of the corresponding peaks in the three traces. A plot of the distance x against the arrival time of successive domains reveals a series of parallel straight lines, one for each domain. The common slope yields for the domain velocity a value of 1.77×10^5 cm/sec, which matches well the sound velocity for shear waves (1.75×10^5 cm/sec). The measured velocity is essentially independent of the pulse amplitude and risetime, the uniformity of the sample or its resistivity. For the semiconducting samples under study, it very nearly represents also the saturated electron drift velocity. The first straight line extrapolates to $x=0$ precisely at $t=0$, while the time-separation T between domains is equal to the sonic transit time through the filament. It follows then that all the domains originate at the cathode, the first at the onset of the pulse* ($t=0$) and each subsequent domain just when the preceding one has moved out of the sample through the anode. These results are similar to those reported by Sliva and Bray[4] for GaSb, and by Haydl and Quate[7] for CdS, and can be similarly accounted for by the fact that the application of the pulse as well as the exit of the high-resistance domains give rise to time-varying gradients in the electric field at the contact region which, as a result, acts as a site of ultrasonic generation. The present data, however, provide a more detailed picture of the process. Since at any instant there is only one domain in the filament, it follows that if its width is smaller than the probe separation, the *peak* probe drop $\delta V_p(t)$ associated with it should represent the *entire* excess filament resistance ΔR at that instant of time, so that

$$\delta V_p(t)=(1+R_0/R_s)\Delta V_f(t)\ ,$$

where $\Delta V_f(t)$ is the voltage across the filament in excess of the ohmic drop. This relation is well satisfied in Fig. 1 ($R_s=R_0$ and $\delta V_p\approx2\,\Delta V_f$), as it does in fact for any other position of the probes and at any time *before* steady-state conditions are approached. Such one-to-one correspondence between $\Delta V_f(t)$ and $\delta V_p(t)$ was found for all samples studied. The domain width, however, varies somewhat from sample to sample (in the range 0.1–0.4 mm), and is a function of the applied field, the sequential number of the domain and its position along the filament. Contrary to the situation in photoconducting CdS, we do not observe current oscillations corresponding to a round trip of sonic flux[9] or of the type reported by Kroger *et al.* and explained by Prohofsky in terms of a collective phonon wave model.[1]

The "square-wave" shape of V_f in Fig. 1 is typical to samples of uniform resistivity and illustrates well the simple character of the flux buildup process. Each domain starts out at a very low flux level and initially ($x\lesssim2$ mm, $t\lesssim1\ \mu$sec) it can neither be detected by the probes nor does it raise V_f above its ohmic value. The flux is strongly amplified by interaction with the drifting electrons until a nonlinear limiting process sets in. And indeed, after a certain time interval, which decreases as expected with increasing pulse amplitude, ΔR rises rapidly to a fairly constant value ΔR_{max} which is maintained until the domain leaves the sample. Irrespective of the pulse amplitude, the value of ΔR_{max} is always such that the domain absorbs the *entire* excess voltage across the filament, leaving the rest of the crystal under a field which is just below threshold. In other words, the buildup of a domain inhibits the amplification of acoustic flux anywhere else in the filament (see below).

Relatively small inhomogeneities in resistivity (less than 10%) may give rise to large undulations in V_f within one sonic transit time. These often appear as "higher harmonies" of the fundamental frequency but in fact they merely reflect the modulation of the amplified flux in a *single* domain due to the variations in drift

* These data were taken with a fast-risetime pulse (0.1 μsec) in order to enable an unambiguous determination of the onset time.

field along the filament. The situation becomes more complicated when gross inhomogeneities are present since these can act as additional sources of acoustic flux.[4]

Steady-state conditions

In sufficiently uniform samples, the pulsed nature of the acoustic flux gradually damps out and the steady-state condition (current saturation) is eventually reached. The decay time is controlled by slight inhomogeneities in the resistivity of the *anode* region, and can assume practically any value between a few sonic transit times and infinity ("continuous oscillations"[10~12]). Thus there is not much point in attempting[13] to correlate the decay constant with fundamental material properties. In fact, even in one and the same filament damped oscillations are often observed for one polarity of the pulse and continuous oscillations for the other, although the difference in resistivity between the two end regions does not exceed several percent. This behaviour can be reversed by changing the cross section of one end of the filament with respect to the other by a comparable percentage. In either configuration, continuous oscillations obtain when the anode region has the lower resistance. Probe measurements reveal in this case that each flux domain is attenuated shortly *before* reaching the anode, as to be expected in view of the lower drift field in that region. Such attenuation of flux *with distance* does not occur in the case of damped oscillations and one is led to conclude that the steady-state condition can be established only when the waves impinging on the anode contact are sufficiently intense so that appreciable flux is reflected back into the sample.

The decay with time of successive flux domains in a *uniform* sample leading to the steady state[14] is illustrated by Fig. 2, where the voltage drop δV across the pair of probes is displayed for two distances of their center from the anode. The decay of δV back to its initial ohmic level in Fig. 2a is typical for probes-to-anode distances larger than about 0.5 mm and indicates clearly the absence of acoustic flux over most of the filament when the steady state is reached. The entire flux is then concentrated in a narrow *stationary* domain close to the anode, as can be seen from Fig. 2b (probes-to-anode distance 0.30 mm), where δV now tends to a considerably higher, nonohmic value. This is shown on a more quantitative basis in Fig. 3, where the *steady-state* potential distribution along the filament (measured with a single probe) is plotted for several values of the drift current I below threshold ("ohmic conditions") and above threshold ("amplifying conditions"). The uniformity of the filament resistivity is apparent from the collinearity of the points under ohmic

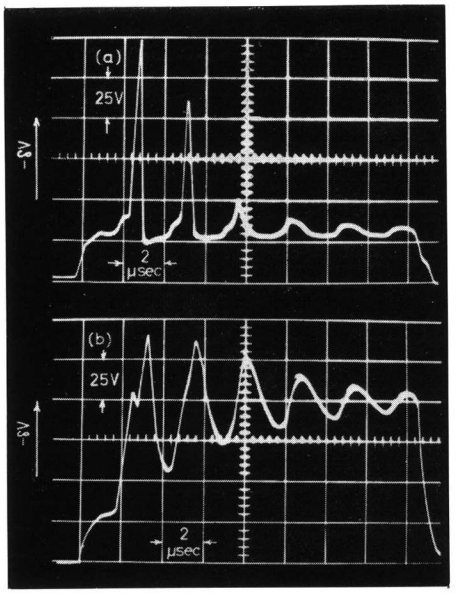

Fig. 2. Potential drop across pair of probes (separation 0.25 mm) for a distance 0.55 mm (a) and 0.30 mm (b) of their center from anode.

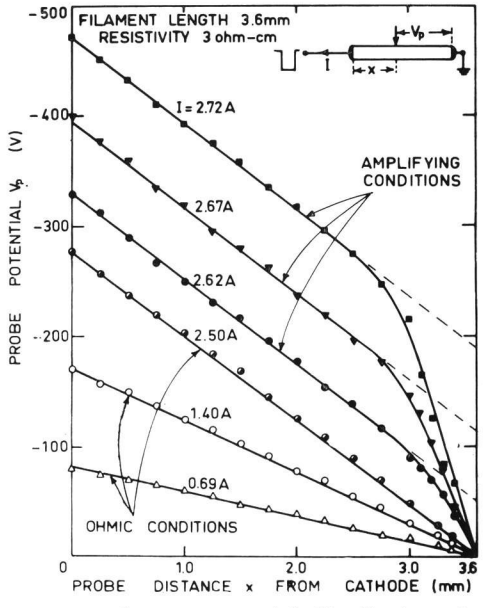

Fig. 3. Steady-state potential distribution along filament for drift currents below and above the threshold value (I=2.50 A).

conditions. In the amplifying state (upper curves), the ohmic field distribution is maintained (the points lie on straight lines)—except near the anode, where the *entire* excess voltage drop occurs. As to be expected, the width of the acoustically-excited anode region increases with increasing drift field. Indications for the concentration of flux near one end of the filament have been found for GaAs,[15] Te[8] and more recently for CdS[6] as well.

As the stationary domain builds up, the field in the rest of the filament gradually decreases until it falls just below threshold and the generation and amplification of additional domains stops. At this stage, the steady-state flux must be derived from continuous amplification of background noise *close to the anode* (the only region where the field is above threshold), part of which is reflected back from the anode (see above). The constant flux level is maintained by a balance between such a buildup process and a nonlinear loss mechanism. The narrow width of the stationary domain is possibly due to the strong attenuation in conducting samples of the reflected flux as it moves against the drift field. This situation is quite different from that observed by McFee[9] for photoconducting CdS, where round-trip gain is possible so that the flux in the steady state is formed by repeated reflections from *both* end contacts and is probably smeared over the entire filament.

Direct evidence for the presence of amplified noise is obtained at higher applied fields. The three traces in Fig. 4 display the probe drop δV in the anode region for three applied voltages. In the lower trace (low field) only the flux domains originating from the cathode are observed. At higher fields the first of these domains is still clearly detectable (at the same time-position) but additional flux, arriving at the probes *earlier*, becomes apparent. This additional flux (which is barely discernible also in Fig. 2 b) must therefore originate *inside* the filament, from a region that extends *closer* to the anode the higher the field (compare the two upper traces). The only source of such flux, originating as it does from an extended region of the bulk, is background noise. As steady-state conditions are approached, amplification of noise becomes the dominant process in establishing the steady-state flux.

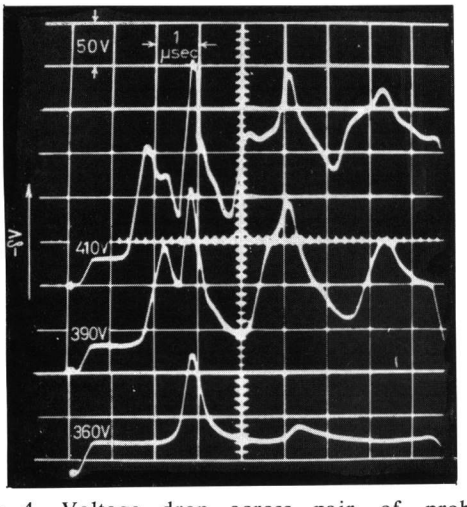

Fig. 4. Voltage drop across pair of probes (separation 0.25 mm) located in anode region for three applied voltages.

The cathode domains can be altogether suppressed if the pulse risetime is increased sufficiently (15–20 μsec). Under these conditions the anode drop, which is now due entirely to amplified noise, rises *monotonically* to its steady-state level.[9] It should be pointed out that in the case of continuous oscillations (no steady-state) the cathode domains cannot be suppressed even for considerably larger risetimes. The generation of the first domain is simply delayed accordingly (and its amplitude is smaller) but the amplitude, width and time relationships of the subsequent domains remain essentially unaltered. This behaviour is markedly different from that reported for photoconducting samples,[1] where current oscillations presumably associated with propagating domains (Type II) could be observed only for risetimes less than 0.5 μsec.

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