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XI-6. Transmission of Microwave Radiation through "Acousto-Electrically Amplifying" CdS

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§ 1. Introduction

In this paper we describe observations made on the propagation of microwave radiation (35 Gc/s) through semiconducting CdS (resistivity $\sim$6 ohm cm) held at room temperature and to which a high voltage pulse has been applied. Our concern is with effects[1,2] observed when, above a field E_k, the sample becomes non-ohmic due to the generation of a large acoustic flux.[3] Striking effects due to crystal non-uniformities are observed and explained using a simple model; these effects include two distinctive oscillation mechanisms. The effect of acoustic flux on the complex permittivity is discussed using an elaboration of the model.

All samples showed a strong saturation of current; for all but one there were oscillations in the current. Quantitative phase shift and attenuation measurements were made on the "non-oscillating" crystal.[5] The deduced real part of the effective microwave conductivity $\sigma_1(\omega)$ is shown in Fig. 1 together with the *dc* conductivity, $\sigma_1(0)=J/E$ where J is the current density. This demonstrates a correlation between the build up in acoustic flux and change in $\sigma_1(\omega)$. (Discussed later).

The fall in $\sigma_1(\omega)$ is primarily manifest through an increase in transmission. In much of this paper we shall be concerned with *qualitative* measurements in which we interpret a rise in transmission as a rise in phonon flux. This interpretation rests on: (1) The results of Fig. 1. (2) "Oscillating" crystals showed time dependent changes in transmission spatially varying in the crystal (established by wave guide narrowed to 0.05 cm). By electrical potential probing a direct correlation was established between a region of increased transmission and a region of abnormally high field. The latter has been interpreted elsewhere as a region of high acoustic flux.[4]

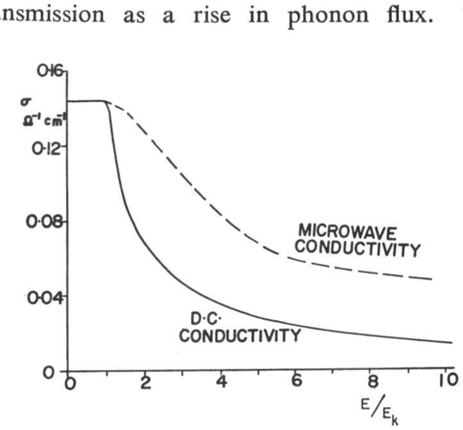

Fig. 1. The *dc* and microwave conductivity as a function of field for 6 ohm cm CdS.

In most of our observations we see regions of increased transmission, of small spatial extent, moving through the crystal. In the light of the above comments we interpret these as regions of abnormally high acoustic flux and term them "phonon packets". It is possible to follow the generation, propagation and destruction of these packets and by the model outlined below describe these processes and their relation to the oscillating current.

In the absence of an applicable non-linear theory the following one dimensional model is introduced. Let the phonon packet of width αL, where L is the crystal length, be situated at $x_1[t]$ at time t. Within the packet it is assumed free electrons of concentration $n(x_1[t])$ are divided into those unimpeded by the acoustic waves, $Fn(x_1[t])$, and those impeded. They contribute $Fn(x_1[t])e\mu E(x_1[t])$ and $(1-F)n(x_1[t])es$ to $J(t)$ respectively, where μ is the ohmic mobility and s the velocity of shear waves. F diminishes as the phonon flux increases. Outside the packet the phonon flux is assumed negligible, thus it is implicit that $F=1$ outside the phonon packet. Then the current density is

$$J(t)=n(x_1[t])\left[\frac{F\mu\langle E\rangle+\alpha s(1-F)}{F\langle 1/n\rangle n(x_1[t])+\alpha(1-F)}\right], \qquad (1)$$

where $\langle\ \rangle$ denotes an average over L and n is assumed constant within the phonon packet. In an elemental volume moving in the same direction as the electrons but with velocity s, the rate of generation of phonon flux due to the acousto-electric interaction is

$$\frac{dN}{dt}(x[t])=cN(x[t])\,[J(t)-n(x[t])es] \qquad (2)$$

This main difference between a linear theory and (2) is the appearance of $J(t)$ in place of $n(x[t])e\mu F(x[t])$. This replacement leads to a natural self limitation of the amplification process by excessive bunching (small F); there is independent experimental evidence for this.[6] Substituting (1) in (2) yields

$$\frac{dN(x)}{dt}=cN(x)n(x_1)e \times\left\{\frac{F[\mu\langle E\rangle-n(x)\langle 1/n\rangle s]+\alpha s(1-F)\left(1-\dfrac{n(x)}{n(x_1)}\right)}{F\langle 1/n\rangle n(x_1)+\alpha(1-F)}\right\}, \tag{3}$$

where the dependence of x and x_1 on t is implicit. These relations suffice to give an understanding of the observations we have made which relate to non-uniformities in the crystal.

§ 2. Observations of Generation, Propagation and Destruction of Phonon Packets

a) Propagation

A phonon packet either propagates towards the anode or remains stationary. Figure 2 illustrates the simultaneous occurrence of both. Once generated a packet propagates through a region of uniform crystal without change in shape or size; there is no change in current. This is consistent with (3) for F small such that a steady state is reached within the packet; outside the growth rate is severely limited, being a factor $N(x_1)/N(x)$ smaller. The velocity of the packet is found to be within 10% of that of shear waves *irrespective of whether the current flows parallel or perpendicular to the c-axis* This provides the first direct evidence that coupling to shear modes travelling within a small angle of the c-axis ($\sim 10°$) is responsible for acousto-electric effects when the current flow is parallel to the c-axis.

When the packet propagates through a region where there is a small *decrease* in conductivity, a fall in current occurs but no detectable change in the packet. The current falls because $F \ll 1$, $J(t) \simeq n(x_1[t])es$ from (1). Outside the packet $dN(x)/dt$ may even become negative since $n(x) > n(x_1)$, see (3). In fact, under these circumstances, the phonon packet acts as a probe on $n(x_1)$ and it has been possible to obtain a direct correlation between local decreases in conductivity and the time variation of saturation current.

When the packet propagates through a region where there is a small *increase* in conductivity, a rise in current occurs accompanied by an

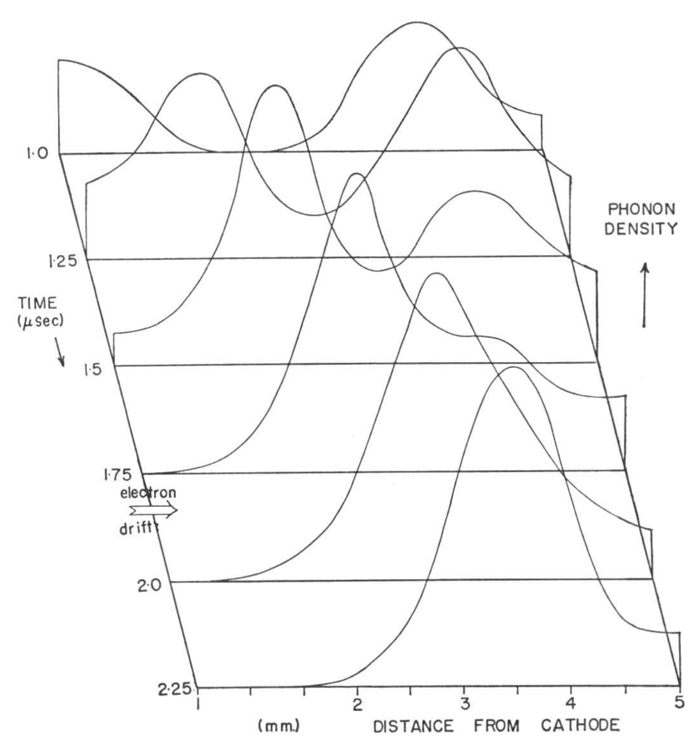

Fig. 2. Propagating and stationary phonon packets in acoustically amplifying CdS.

increase in phonon flux throughout the crystal but a decrease in amplitude of phonon packet. From (1) we should expect the rise in current. But as the current rises, rapid growth of outside the packet occurs ($n(x)<n(x_1)$ in (3)). The increase in N outside the packet now contributes to limit the current so that $J(t)-n(x_1[t])es$ may become negative with consequent decay of the packet. Once through the high conductivity region the packet rapidly regains its original amplitude and once more controlls the current.

b) Generation: Cathode generation

Extrapolation in space and time reveals that the propagating packet shown in Fig. 2 originated in the vicinity of the cathode surface when the high voltage pulse was applied to the crystal. Presumably this is the same type of phonon packet as appears to be entirely responsible for effects in uniform resistivity crystals.[1,4] In our material it is only generated when the external voltage is applied and is not observed in all crystals whereas repeated ge-

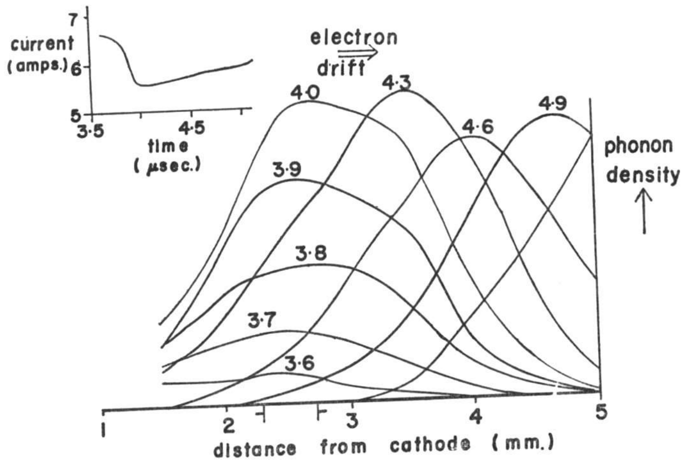

Fig. 3. Generation of a phonon packet at a non-uniformity near the cathode of a CdS crystal. (Numbers are time in μ sec).

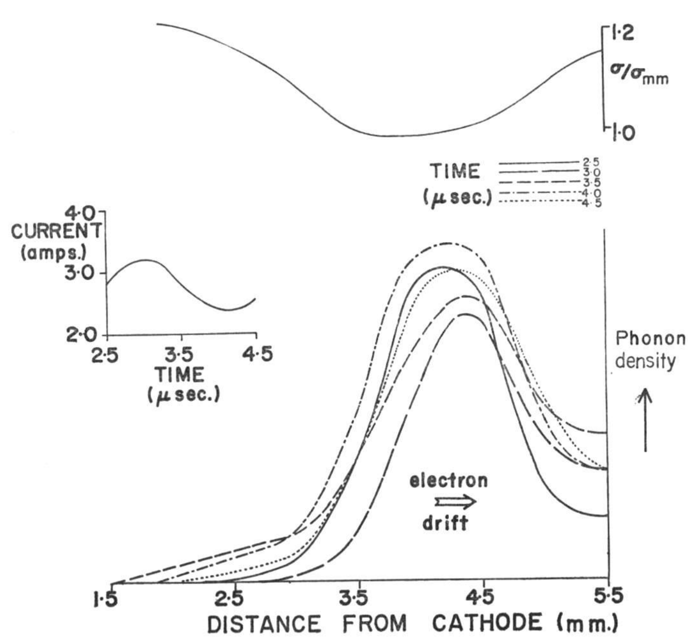

Fig. 4. Temporal and spatial variations in phonon flux at a non-uniformity near the anode of a CdS crystal.

neration, and the accompanying oscillations in current, is associated with non-uniformities which are of large rscale than those discussed under (a).

Generation at non-uniformities

Figure 3 shows the behaviour around a region of low conductivity *near the cathode* (2.5 mm). A strong build up of acoustic flux occurs at the non-uniformity, it propagates as a phonon packet to the anode when, on its destruction, the cycle repeats. Immediately following destruction the current is high ($\alpha \rightarrow 0$ in (1)), the whole of the crystal is amplifying but the most rapid increase in N occurs where n is lowest (2) *i.e.* at the non-uniformity. As the flux builds up, the current falls until there is no detectable change in N during a transit time across the non-uniformity. Then the already generated phonon flux propagates away in the form of a packet, controlling the current at a low level till the packet is destroyed. Then the current rises and the cycle repeats.

If such a region of low conductivity occurs *near the anode* the behaviour is different because destruction at the anode prevents the phonon flux outside the non-uniformity from controlling the current. Figure 4 shows this behaviour. In this extensive non-uniformity a stationary phonon packet is produced (from the time the field is applied, Fig. 4 is an extension in time of Fig. 2) which controlls the current. Any change in current affects the spatial extent of the amplifying region of the crystal, extending it towards the cathode as the current rises (3). Continuous oscillations in phonon flux and current can then occur due to the transit time build-up of acoustic flux and feed back through the current. This is basically the same mechanism as that considered in non-uniform photoconducting material.[7,8]

These two distinctive types of generation can be produced by the same low conductivity region near the end of the crystal simply by reversing the polarity of applied voltage. Similar results have been produced by cutting slots of carefully chosen size in the side of the sample, reducing the cross-section and raising the local (J—nes).

c) *Destruction*

Destruction of the phonon packet occurs when it reaches the anode, and is accompanied by a rise in current (eq. (1), $\alpha \rightarrow 0$). Details of this process are unknown to us since our experimental technique does not allow observations near the contacts.

Destruction of a phonon packet can occur at a non-uniformity. This is shown in Figs. 2 and 4. The propagating packet merges with stationary packet generated in the extensive non-uniformity referred to above. There is little change in amplitude on merging consistent with the assumption of saturation in N. Once the propagating packet is in the low conductivity region then the current is controlled entirely by it. We must assume that because of the extent of the non-uniformity N can rise sufficiently high *within* it to hold the current at a low level forcing the rest of the crystal to attenuate.

§ 3. Microwave Propagation in the Presence of a High Acoustic Flux

From Fig. 1 we note that $\sigma_1(\omega)=\sigma_1(0)$ for $E<E_k$, consistent with $\omega\tau \sim 10^{-2}$ for CdS at room temperature. For $E>E_k$, $\sigma_1(\omega)>\sigma_1(0)$ and it was found also that

$$\left|\frac{\delta\sigma_1(\omega)}{\sigma_1(\omega)}\bigg/\frac{\delta\varepsilon_1(\omega)}{\varepsilon_1(\omega)}\right| \equiv \chi \simeq 4 \,,$$

where $\varepsilon_1(\omega)$, the real part of the permittivity, contains both lattice and free carrier contributions.

If the additional flux generated above E_k is regarded as an added source of scattering (albeit into a reference frame moving with velocity s), it is predicted that $\sigma_1(\omega)<\sigma_1(0)$ in direct contrast with observations.

Reverting to the classical model introduced earlier we note that the bunching of carriers in potential minima will produce planes of constant permittivity normal to which (and parallel to the microwave E) the permittivity varies periodically. Simulating this variation by a laminated structure, $\varepsilon^{(p)}$ alternating with $\varepsilon^{(t)}$ of respective widths l_p and l_t ('t' characteristic of potential trough, 'p' characteristic of potential peak), leads to an effective ε[9]

$$\varepsilon=\frac{\varepsilon^{(p)}\varepsilon^{(t)}(l_p+l_t)}{\varepsilon^{(p)}l_t+\varepsilon^{(t)}l_p}\,, \tag{4}$$

since l_t and l_p are very small relative to the microwave wavelength. $\varepsilon^{(t)}$ contains a contribution from bunched carriers while $\varepsilon^{(p)}$ does not, both are readily obtained following the arguments leading to (1). Using (4) it is possible to simultaneously fit the $\sigma_1(0)$ and $\sigma_1(\omega)$ data provided $l_p/l_t \geq \sqrt{3}$. However, $\chi<2$.

An interesting feature which this model overlooks is a resonance of carriers impeded by the lattice waves about the potential minima produced by the combined fields of bunched carriers and lattice wave. The resonant frequency would depend of the magnitude of the potential and the acoustic wavelength; its incorporation in $\varepsilon^{(t)}$ is straightforward for a given acoustic mode. An investigation of the consequences of this are incomplete but it may account for the behaviour of χ.

It is a pleasure to acknowledge valuable discussions with Dr. E. A. Ash and Professor N. I. Meyer.

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DISCUSSION

Kikuchi, M.: What kind of factor determines the period of the continuous oscillation?

Paige, E.G.S.: Extent of none uniformity.

Kikuchi, M.: Was the period of oscillation dependent on any factors, such as bias voltage etc.?

Paige, E.G.S.: Only weakly.

Meyer, N.I.: In connection with the question about stable or non-stable current saturation it might be of interest to mention that we have measured current saturation as a large number of semiconducting ZnO crystals, and in nearly all cases was the saturation stable over a large field region.

Yamashita, J.: I am puzzling about the condition. Under what condition do we have a moving domain, or a stationary saturation current? What is your opinion about this?

Paige, E.G.S.: In our samples it is very unusual to see a stationary current saturation. Even when the phonon packet is "stationary" then, as shown in the last figure, fluctuations in shape are occurring which lead to current oscillations.

To obtain stability it is probably necessary (1) to have a uniform crystal to elliminate non-uniform amplification and (2) to apply the voltage slowly to elliminate shock excitation.

Murayama, Y.: If there is any experimental evidence that the high density CdS samples ($\sigma \sim 10^{-1} \Omega^{-1}\,\mathrm{cm}^{-1}$) are different from the low density ones ($\sigma \lesssim 10^{-4} \sim 10^{-5}\,\Omega^{-1}\,\mathrm{cm}^{-1}$) in their features of the motion of domains, isn't the quantity of carrier injection critical to the difference?

Paige, E.G.S.: If by carrier injection you mean the carrier concentration, the answer is yes.

Müller, G. O.: What is the extent inhomogeneity (spatial dimensions and percentage) necessary for your mechanism to work. I'm specially interested in your opinion, whether a dislocation will give enough inhomogeneity or not.

Paige, E.G.S.: In high conductivity material a fluctuation in conductivity of about 5% or more extending over a distance $\sim s\tau$ where s is the shear wave velocity and τ is a build up time of acoustic flux is required. This leads to distances very large compared with the dimensions of non-uniformities ($\sim 10\,\mu$m) associated with an isolated dislocation.