INTERACTION OF ELECTRONIC CURRENT WITH HYPERSONIC WAVES IN SOLIDS

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Summary

Since the last report considerable progress has been made with the construction of apparatus for experimental work, and some data have already been obtained. On the theoretical side, an attempt has been made to relate the radiation effects in CdS with phenomena seen in gallium arsenide and indium antimonide. It is hoped that a unified treatment of the effects of high electric fields on these materials may be produced. A preliminary approach to a large-signal analysis has been made, and it is surmised that the current saturation in CdS is probably due to electric, rather than acoustic, saturation. The acoustic flux associated with the current saturation effect has been observed experimentally, and frequency components have been seen which are unexpectedly low in frequency.

I. Discussion

As was stated in the first Quarterly Report, the current saturation effects seen in cadmium sulphide were chosen as one of the principal subjects for study during this quarter. Associated with this saturation is the build-up of acoustic flux in the crystal. Normally this flux is incoherent but occasionally coherent sinusoidal oscillations have been seen. Clearly a study of the acoustic activity in CdS under these conditions is vital to our understanding of the physical processes involved.

In addition, we suggest that there is the possibility of a connection between this fluctuation phenomenon and some other more recently discovered effects in indium antimonide and gallium arsenide. Because of the similarity in behavior the work on InSb and GaAs may be helpful in reaching an understanding of CdS. We deal below with these three semiconductors separately, but first make some general remarks on the frequency dependence of the noise observed.

Propagating space-charge waves on the carriers in a semiconductor can exist, but only at a plasma frequency high compared to the collision frequency. An analysis[1] of these waves shows that the damping is frequency sensitive, and that a good approximation to the frequency of least damping is:

$$\omega_0^2 = \left[\frac{e v_0^2 \sigma}{\epsilon k T \mu}\right] \tag{1}$$

where

e = electron charge

σ = conductivity

μ = mobility

v_0 = d.c. drift velocity of the carriers.

This relation also gives the frequency of maximum gain for acoustic amplification in cadmium sulphide as predicted by White,[2] but we can see that Eqn. (1) has broader implications. It predicts that if the electrons, drifting through the semiconductor, are excited by r-f power over a broad band, whatever the source of the excitation, then the r-f current will have a peak at frequencies around ω_o, as given by Eqn. (1).

Alternatively, if the current waves are coupled to the lattice or to some other non-dispersive wave-propagating system, we can expect the combined system to have a peak in its output near ω_o. This, of course, is precisely what is predicted by White's analysis, with the sound waves forming the second system.

Bearing these general observations in mind we now discuss separately the three semiconductors under consideration.

(a) Cadmium Sulphide

It has been found [(1),(3)] that associated with the current saturation, there is a buildup of incoherent acoustic energy in the crystal. The spectrum of this signal has a peak near the frequency given by Eqn. (1). It has been suggested that this indicates that the crystal under test is oscillating due to some internal feedback mechanism. The details, however, are by no means clear:

Firstly, if we consider that the crystal slab is acting as a resonant cavity, albeit many wavelengths long, then, given enough time for the oscillation to build up to saturation amplitude, one would expect the cavity to operate at a single frequency. In a typical experiment [(4)] at 60 Mc/sec., the signal was seen to die away with a time constant of about 70 µsecs. If we were measuring the Q of a cavity by watching the decay of oscillations, we would apply the formula, $\tau = Q/\omega_o$, and obtain Q = 26,000. Thus even with a cavity a dozen wavelengths long, with several closely spaced resonances, we would anticipate that one would eventually dominate. We recognize, however, that the mode spacing may be small that the Q of adjacent modes may not differ greatly, and a small anharmonicity of the crystal may couple modes.

Secondly, the signal seems to build up from an extremely high initial level. If the signal is due to the mechanism described by White et al., then its initial level should be of the order of $kT\Delta f$, provided that the frequency is high enough. (At low frequencies, photocurrent or contact noise can dominate and set the initial level. We discuss this in Section II in relation to our own exper[illegible]). In the experiments mentioned[4], the initial noise level was some 80 db. above $kT\Delta f$ (referred to the input terminals). The output noise level was 20-30 db below the saturated output power. This surely needs explanation.

In the past few months, Dr. E. W. Prohofsky, of the Sperry-Rand Corporation has proposed a new explanation[5] for the non-ohmic behavior of CdS. He suggests that it is due to phonons in the frequency range 10^{10}-10^{11} c.p.s., i.e., in the upper microwave region, rather than the megacycle range as predicted by White's theory. His theory is of considerable interest to us, since it does not appear to require electron bunching. But, as Prohofsky points out, it is very difficult, with present transducer techniques, to detect these phonons if, in fact, they are being generated.

A cursory examination of methods of looking for phonons at about 10^{10} c.p.s. reveals the following possibility:

A new type of photo-detector, called the "Lasecon", which can detect light modulation at microwave frequencies, typically those around 10^{10} cycles per second, was recently developed at these Laboratories[6]. It should therefore be possible to illuminate a CdS crystal in the current-saturated regime with a laser beam and to detect microwave modulation on the reflected light.

Shockley[7], in his classic paper on "hot" electrons, tried to account for non-ohmic behavior in germanium at moderately-high electric fields. Using a "billiard ball" model to describe the electron-phonon collisions, he predicted that the break-point in the V-I curve would occur at a field in which the electron drift velocity would be 1.5 v_s. However, Smith has shown from many experiments that the break-point in CdS occurs at $v_d = v_s$. Thus Shockley's theory, as originally formulated, does not explain the phenomenon, but it may be possible to modify the theory. In CdS, the phonons are not of the same type as in Ge. They are, in fact, "piezons", or piezoelectric phonons, and existing theories have not been able to describe the electron-piezon interaction at normal temperatures, i.e., one cannot compute the coupling coefficient, $e^2/\epsilon C$, from first principles. Th... ...ficulty has been pointed out by Ashley.[8]

(b) Gallium Arsenide

Coherent oscillations in the current passing through GaAs under high-field conditions have been observed by Gunn[19] at I.B.M. They have also been seen at M.I.T. The waveforms produced seem more like those of relaxation oscillations than sine wave oscillations. Workers at RCA Laboratories have yet to reproduce these results. We have, however, been able to produce radiation of an incoherent character under high-field conditions.[10] Noise was detected over the range 0.5 - 4.0 kmc/sec. On calculating the frequency, ω_o, from Eqn. (1), using the experimental values of field and conductivity, a value of 14 kmc/sec. was obtained for T = 300° K. This value, however, is based upon a field-independent mobility and could be lower.

Nevertheless, there are some dissimilarities between the conditions in GaAs and in CdS. In GaAs, the threshold voltage is much sharper and the electron velocity, assuming constant mobility, is higher than the velocity of sound. On the other hand GaAs is structurally similar to CdS, and is also piezoelectric, although less so than CdS.

The point we wish to make is that this is an example of incoherent radiation from a semiconductor at frequencies tolerably near to that predicted by Eqn. (1), but under conditions where present theory predicts no acoustic gain. It suggests that such radiation, e.g. in CdS, need not rely on acoustic wave amplification for its existence. Nevertheless, the fact is that in CdS the electron drift velocity is close to the sound velocity when the radiation is observed, i.e., conditions are appropriate for acoustic gain.

There is, however, another similarity between GaAs and CdS which should be considered. Smith and Moore[11] in this laboratory have observed current oscillations in CdS under high-field conditions (c.f.Gunn's experiments). There seems to be a strong possibility that the two phenomena have common roots. We are therefore contemplating acoustic experiments in GaAs, similar to those with CdS.

(c) Indium Antimonide

Experiments in this laboratory by M. C. Steele and R. D. Larrabee have detected microwave radiation from InSb in the 10-30 kmc/sec region.[12]

At first sight, these experiments appear to have little in common with those on CdS and GaAs. A magnetic field is required, preferably perpendicular to the electric field. Also, the presence of electrons and holes is required. However, from conversations with Dr. Steele, some interesting points emerged.

Under the conditions described, a Hall field is generated in a direction perpendicular to the electric and magnetic field. A space charge distribution is set up in the crystal and the initial motion of the electrons in this direction is halted by the space charge forces. On the other hand, if a hole and an electron move together, there is no net transfer of charge and the space charge is not disturbed. Since the electron is more mobile than the hole, it is not unreasonable that the net mobility of the pair will be near that of the hole alone.[13] When a calculation of electron drift velocity was made, using this assumption, it was found to be very close to the velocity of sound. Moreover, the value of ω_o was a little below 10 kmc/sec.

These figures may be coincidental, but in addition Larrabee[12] has observed current oscillations in InSb crystals, not unlike those seen in CdS my Moore and Smith. In both cases the frequency of oscillation is related to a dimension of the crystal. In CdS, it seems to be dependent on the transit time along the crystal. In InSb, it corresponds roughly to an electron transit time across the crystal, i.e. in the direction of the Hall field. Any results relevant to CdS will be reported with the kind permission of Larrabee and Steele.

In summary, there appears to be a more than superficial connection between previously unrelated phenomena in CdS, GaAs, and InSb. The similarity is greatest between CdS and GaAs.

II. Experimental Work

Three CdS crystals of various purity grades have been obtained. These have been sliced (see Photo 1) to provide, from each crystal, samples 0.5 mm and 5 mm thick. (The load on our Solid-State Processing Department is heavy, so that delivery of cut samples is slow, but this situation is being rectified). Transducers have just been delivered, and the construction of "amplifiers" is under way. The slices will be used to investigate the dependence of signals, coherent and/or incoherent, on such parameters as conductivity, crystal length and injected signal level, bearing in mind the remarks made in Section I.

To expedite the experimental work, one transducer, of unknown quality, was obtained from another source and used to test the capability of the laboratory facilities in making indium bonds. (Photo 2). This trial run seems to have been accomplished successfully and some interesting results have been obtained with this crystal-transducer combination.

The transducer was bonded with indium to a CdS slice, 0.5 mm thick. The crystal was, in turn, bonded to a transistor header to provide a heat sink and an electrical contact. (Photo 2).

Initially, pulsed voltages of up to 100 V (500 μsec long) were applied to the crystal, and the acoustic output from the transducer was observed on an oscilloscope. The applied voltage corresponded to the knee of the V-I curve. (Fig. 1). The experimental circuit is shown schematically in Fig. 2.

Fig. 3(a) shows the output from the transducer at 100 V, which was the voltage at which the crystal current saturated. Since the noise appeared to have low-frequency components of considerable amplitude, "single shot" photographs had to be taken in order to resolve any details.

Fig. 3(b) shows the initial transients in the output from the transducer.

Fig. 3(c) shows the output during one complete pulse.

The low-frequency components interested us greatly, since they cannot be easily explained from existing theories. Accordingly, some experiments were performed with d.c. voltages applied. While this eventually proved fatal to the crystal, some interesting results were obtained. (Figs. 3(d), 3(e), 3(f)).

Fig. 3(d) shows a single slow sweep of the oscilloscope. The time taken for one sweep was 1 second and it can be seen that there are components of noise at 2-3 cycles / sec.

Figs. 3(e) and 3(f) were taken under similar conditions, but with faster sweep speeds.

No components could be seen much above 1 megacycle per sec., but no attempt had been made to tune out the capacitance of the transducer and the oscilloscope, so this is probably not significant. Unfortunately the crystal failed before further work could be done.

Until these experiments can be repeated and confirmed with similar crystal slices, we should be cautious in reading too much into them. Nevertheless they suggest that the current saturation in CdS is due to a random, incoherent collision process, and not to a mechanism involving bunching of the carriers as we now understand bunching.

The failure of the crystal and the resultant change in the V-I characteristic are illustrated by Fig. 1. Evidently overheating, due to the dissipation of some 40 watts per cubic centimeter had caused the generation of electron traps, and a typical trap-controlled current curve[(14)] resulted. The experimental points in Fig. 1 were taken with continuous voltages applied, but the current was measured before the crystal had time to warm up appreciably.

For comparison, some current-voltage characteristics were taken by applying saw-tooth voltage pulses to the crystal. It was found that the current was affected by the pulse length, and increased with it. We interpret this by proposing that, since the traps take a finite time to fill, and this time is less than the transit time, the number of filled traps, and hence the chance of trapping, will vary after the voltage is applied. As the traps are filled, the chance of an electron falling into one is decreased, and the current increases.

When plotted on log-log graph paper, (see Fig. 4), the current was found to be increasing roughly as $V^{7/4}$.

No detectable output could be seen from the transducer after the crystal had failed. Since the field, and drift velocity, vary through the length of the crystal in the trap-controlled regime, this is not unreasonable. Instead of traveling with a velocity greater than v_s throughout the crystal, the electrons will only do so through a smaller region near one end, since the trapped space-charge will depress the voltage inside the crystal. (c.f. space charge limited diode).

In conclusion, it seems that the behavior of the crystal can be accounted for reasonably well, and that the signals seen under current-saturated conditions were not spurious, e.g. contact noise. We have three main reasons for believing this:

1) The noise appeared at a threshold voltage near the predicted value.

2) No noise could be seen on the input voltage pulses.

3) The noise disappeared when the crystal failed.

Nevertheless, our most urgent project is to repeat and confirm this experiment with transducers of known quality.

An attempt will be made to detect X-Band radiation from a post of cadmium sulphide located in an X-Band waveguide (Fig. 5). A sample is being prepared which has a value of ω_o at about 8 kmc/sec. Measurements will also be made of the microwave impedance as a function of applied d.c. electric field. (The waveguide mounting is preferred to the cavity mentioned in the first Quarterly Report, as it was found easier to mount samples in the former).

III. Analysis

The usual analyses[1,2] of electron-acoustic wave interaction assume, for simplicity, a one-dimensional configuration. This precludes the existence of an external r-f circuit and, indeed, in these analyses the total r-f current is taken to be zero. In practice this is not the case, and, in fact, the r-f current in the external leads may be as important an experimental measure of the electron-acoustic activity as is the acoustic flux in the transducer circuit. The total r-f current is estimated in the following brief calculation and the results are discussed. In addition, the calculation forms the basis of an analysis of the complex r-f impedance of the active crystal. This impedance calculation will be pursued in detail during the next Quarter.

The total r-f current density, I, is the sum of the carrier current density, J, and the displacement current density $\partial D/\partial t$. Thus

$$I = J + \partial D/\partial t \tag{1}$$

where J is due to convection current and diffusion current:

$$J = \rho v - D_n \frac{\partial \rho}{\partial x} \tag{2}$$

Here ρ is the charge density of the mobile carriers, v is their drift velocity and D_n is the diffusion coefficient. For a mobility-dominated flow,

$$v = \mu E \tag{3}$$

If a time dependence of exp $(j\omega t)$ is assumed and if the system is linearized, them with r-f terms denoted by subscript-one and d.c. terms by subscript-zero, one has that

$$\begin{aligned} I_1 &= J_1 + j\omega D_1 \\ &= \mu(\rho_0 E_1 + \mu \rho_1 E_0) - D_n \frac{\partial \rho_1}{\partial x} + j\omega D_1 \end{aligned} \tag{4}$$

The r-f electric displacement is given by Poisson's equation:

$$\frac{\partial D_1}{\partial x} = \rho_1 \tag{5}$$

Furthermore, this displacement is related linearly to the r-f field intensity by

$$D_1 = \epsilon' E_1 \tag{6}$$

where the effective dielectric constant reduces to the "cold" dielectric constant, ϵ_o, in the absence of electron-acoustic interaction. Thus Eq. (4) becomes

$$I_1 = (\sigma_1 + j\omega\epsilon')\,E_1 + \epsilon'\left(v_o \frac{\partial E_1}{\partial x} - D_n \frac{\partial^2 E_1}{\partial x^2}\right) \qquad (7)$$

where the conductivity is $\sigma = \mu\rho_o$ and the d.c. drift velocity is $v_o = \mu E_o$.

Since I_1 is not a function of distance, Eq. (7) must have a solution of the form

$$E_1 = \mathcal{E}_1 + \mathcal{E}_2(x) \qquad (8)$$

where

$$I_1 = (\sigma + j\omega\epsilon')\,\mathcal{E}_1 \qquad (9)$$

and

$$0 = (\sigma + j\omega\epsilon')\,\mathcal{E}_2 + \epsilon'\left(V_o \frac{\partial \mathcal{E}_2}{\partial x} - D_n \frac{\partial^2 \mathcal{E}_2}{\partial x^2}\right) \qquad (10)$$

Equation (9) contains the main point of this calculation. It is that the total r-f current is a function of the perturbed dielectric constant, ϵ', and so a measurement of this current in the external circuit should exhibit effects due to acoustic amplification. So far such measurements, made here and elsewhere, have been inconclusive. If further tests bear out the preliminary finding that no such acoustic effects appear, then further doubt is to be cast on the linearized theory that has been traditional in this problem.

Furthermore, a linear theory cannot predict the saturation level of the acoustic effects; the saturation level is established by non-linearity somewhere in the system. As was noted in the first Quarterly Report, the non-linearity may lie in the acoustic system or in the electrical system. Intuitively one feels that it lies in the electrical system. However, the possibility of acoustic saturation needs examination. A first step in this direction is outlined in Appendix A, where the binding energy of CdS is computed from the Madelung energy and by a Born-Haber cycle. The results agree as well as can be expected when van der Waals and polarization contributions are neglected. The former computation may be extended to get an indication of the non-linearity of the force function.

IV. Plans for the next quarter

We plan to continue our study of the relationship between the current saturation phenomenon and acoustic signals in the crystals, both internally generated and injected via transducers. Specifically, we hope to:

1) Study the relation between spontaneous current and acoustic signals to reach an understanding of these.

2) Study the microwave properties of CdS to obtain direct evidence of the role of high-frequency phonons in current saturation and spontaneous oscillation. Contemplated experiments include determination of the effects of sample geometry and microwave measurements of sample impedance with and without an acoustic driving signal.

The program has been carefully chosen to complement but not overlap, the work of Smith and Moore in the Laboratory so that a maximum of information is obtained in a short time.

References

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(9) J. B. Gunn, Paper presented at Electron Devices Conference, Washington, D. C., 1963.

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(11) R. W. Smith and A. R. Moore, Private Communication.

(12) R. D. Larrabee, Private Communication.

(13) M. C. Steele and Takeo Hattori, "Generation of Sound Waves by a Self-Pinched Plasma in a Solid," J. Phys. Soc. Japan, Vol. 17, p. 1661, 1962.

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Appendix A

The relevant data are to be found in Seitz, "The Modern Theory of Solids," McGraw-Hill, New York, 1940.

a) Madelung computation.

The binding energy is given by

$$\mathcal{E} = \alpha_M \frac{q^- q^+}{a} - \frac{\beta}{a^n} \tag{1}$$

$$= \alpha_M \frac{q^- q^+}{a}\left[1 - \frac{1}{n}\right]$$

where

α_M = Madelung constant

= 1.64 for zincblend or wurtzite structures

q^- = charge of negative ion

q^+ = charge of positive ion

a = lattice opening

= 2.52 Å in CdS

β = repulsive force constant

n = 9 for sulphides

Since Cd and S are divalent

$$\mathcal{E} = \frac{4\alpha_M q^2}{a}\left[1 - \frac{1}{n}\right]$$

= 33.3 electron volts.

where q is the electronic charge.

b) Born-Haber cycle.

1. Energy to form $Cd^{++}(g)$ from Cd(S), where g denotes gas, s solid and a minus sign on the energy means energy supplied to the system.

$Cd(S) \rightarrow Cd(g)$	-1.17 ev	Heat of subl.
$Cd(g) \rightarrow Cd^+(g)$	-8.99 ev	First ion.
$Cd^+(g) \rightarrow Cd^{++}(g)$	-16.8 ev	Second ion.
$Cd(S) \rightarrow Cd^{++}(g)$	-26.96 ev	

2. Energy to form $S^{--}(g)$ from $S(s)$

$S(s) \rightarrow S(g)$ -5.90 ev Heat of subl.

$S(g) \rightarrow S^{-}(g)$ +2.5 ev First affinity.

$S^{-}(g) \rightarrow S^{--}(g)$ -3.25 ev Second affinity.

$S(s) \rightarrow S^{--}(g)$ -6.65 ev

3. Heat of formation of CdS

$Cd(S) + S(s) \rightarrow CdS + 1.48$ ev.

4. Binding energy

$Cd^{++}(g) + S^{--}(g) \rightarrow CdS + 35.0$ ev.

The binding energy of 35.0 ev is in reasonable agreement with the value of 33 ev obtained from the Madelung calculation.

A first-order expansion of Equation (1) yields the compressibility, second- and higher-order expansions yield the nonlinear terms.

Figure Captions

Photo 1 Crystals of CdS and transducers for 45 Mc. Note small thickness (0.002") of the transducer.

Photo 2 Transducer and crystal of CdS mounted on transistor header.

Fig. 1 Current-Voltage characteristics of the crystal, before and after failure.

Fig. 2 Schematic of experimental set-up.

Fig. 3 Transducer output versus time.

Fig. 4 Characteristics of the failed crystal.

Fig. 5 Sample mount for CdS r-f impedance measurements.

Key to Figure 3

Fig. No.	Voltage Applied	'Scope Sensitivity	Sweep Speed
3(a)	100 V Pulse	0.2 V/cm	100 μsec/cm
3(b)	100 V Pulse	0.2 V/cm	10 μsec/cm
3(c)	100 V Pulse	0.2 V/cm	100 μsec/cm
3(d)	300 V D.C.	0.05 V/cm	100 msec/cm
3(e)	300 V D.C.	0.05 V/cm	1 msec/cm
3(f)	300 V D.C.	0.05 V/cm	100 μsec/cm

For further details see the text.

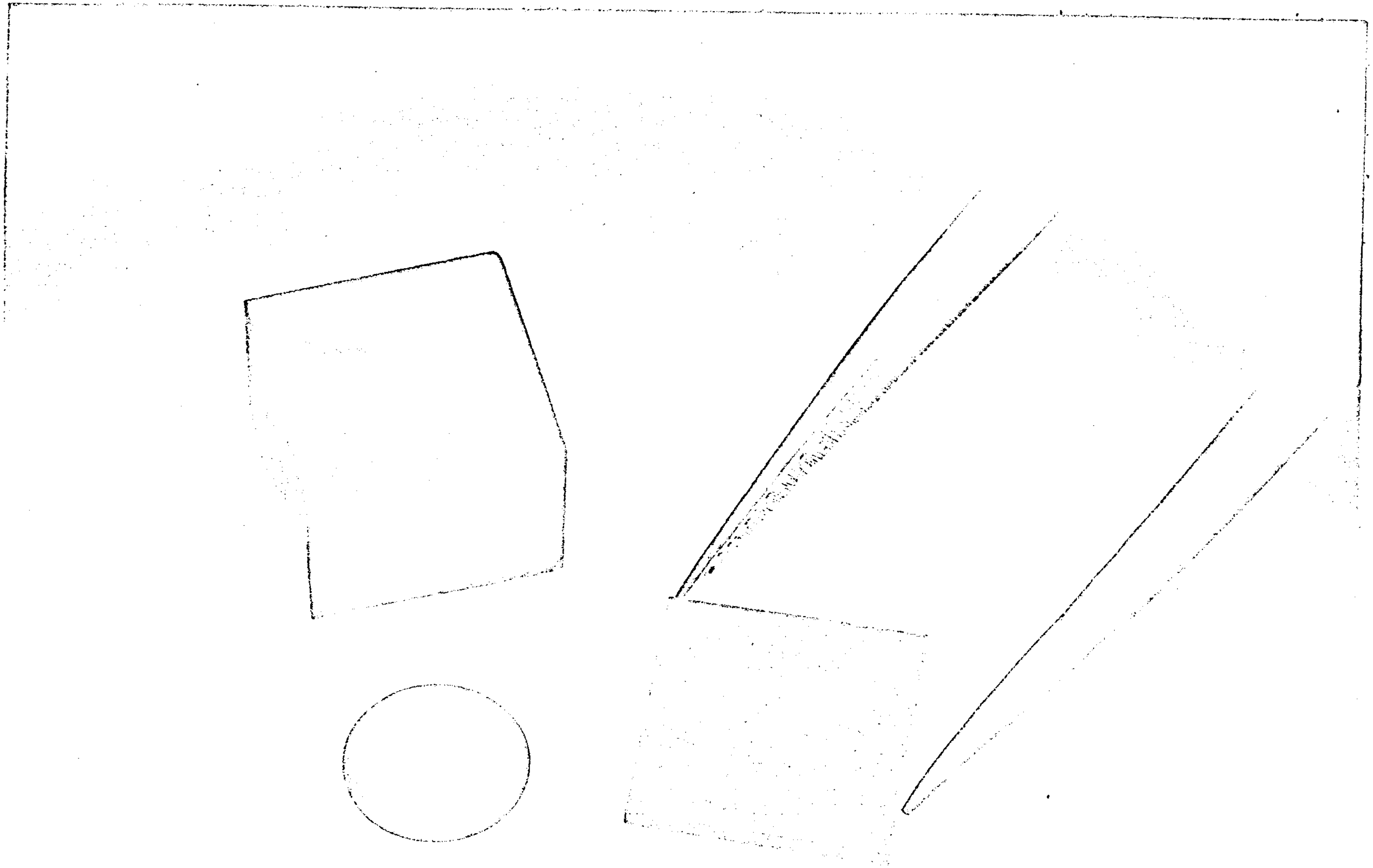

PHOTO. I. CRYSTALS OF CdS AND TRANSDUCER FOR 45 MC/SEC. NOTE SMALL THICKNESS (0.002 OF THE TRANSDUCER)

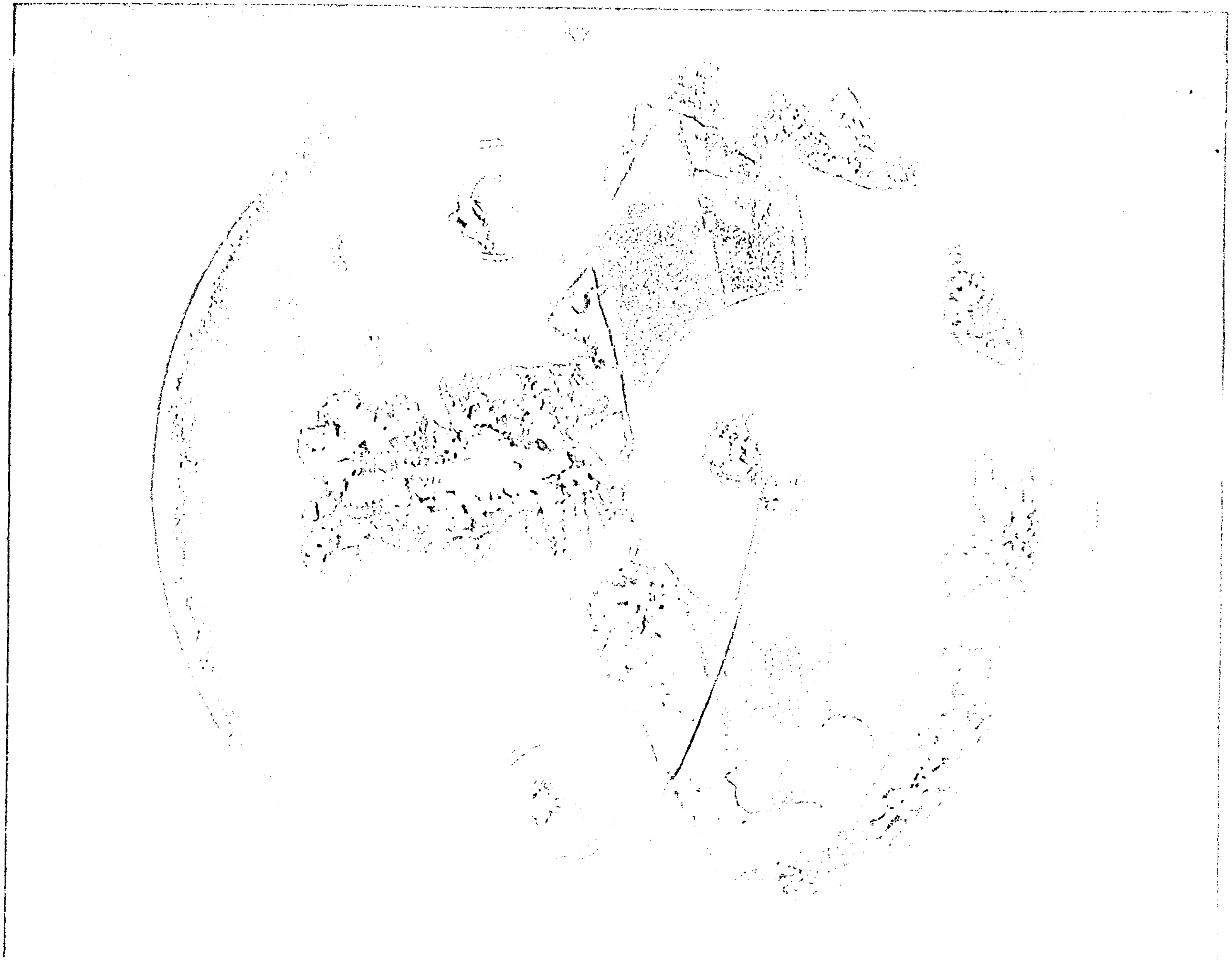

PHOTO. 2. TRANSDUCER CRYSTAL OF CdS MOUNTED
TRANSISTOR HEADER.

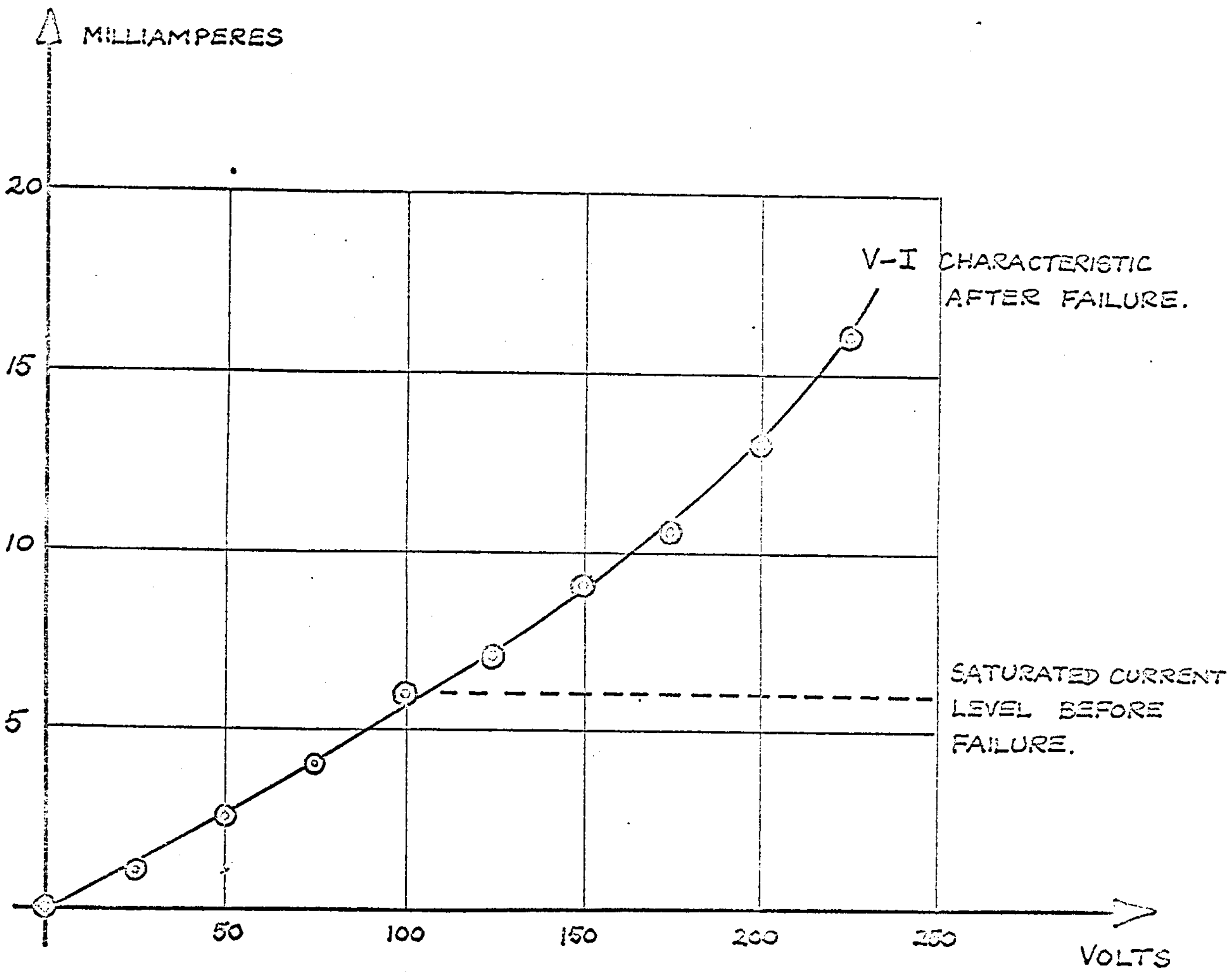

FIG. 1. CURRENT – VOLTAGE CHARACTERISTICS OF THE CRYSTAL, BEFORE AND AFTER FAILURE.

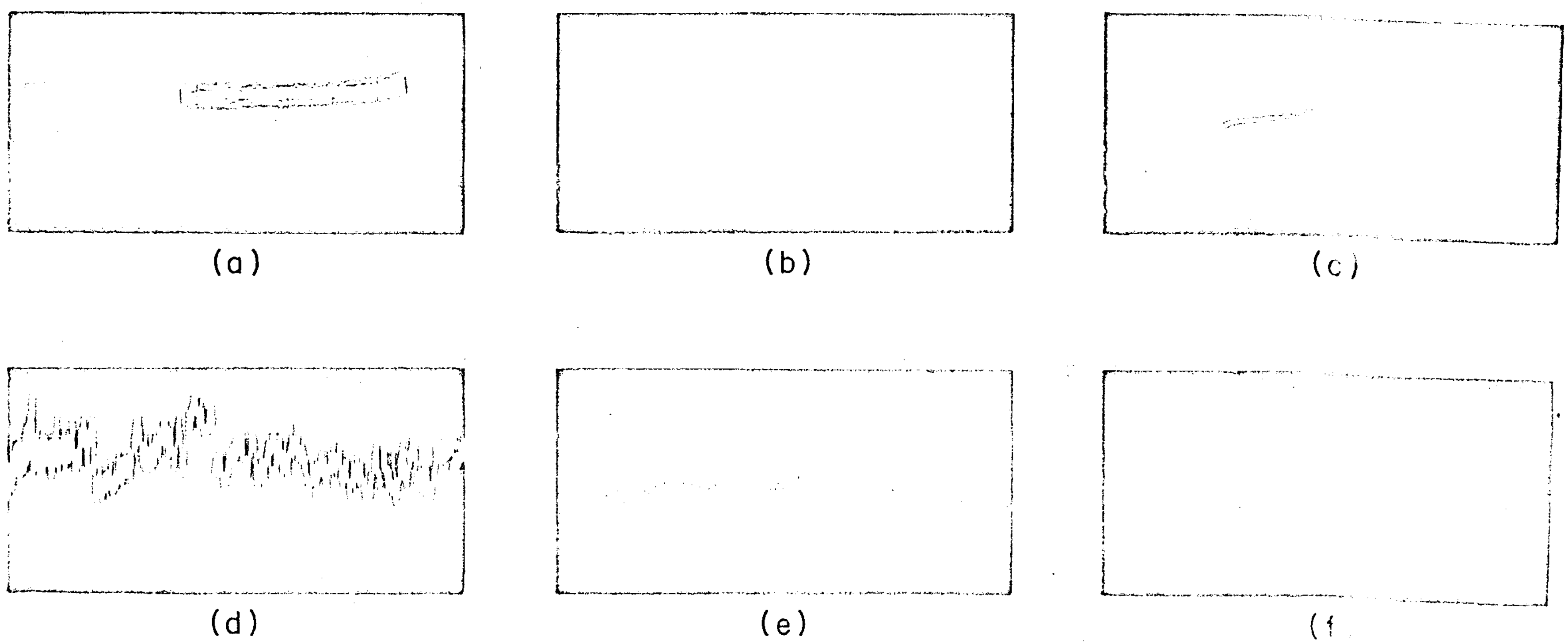

FIGURE 3

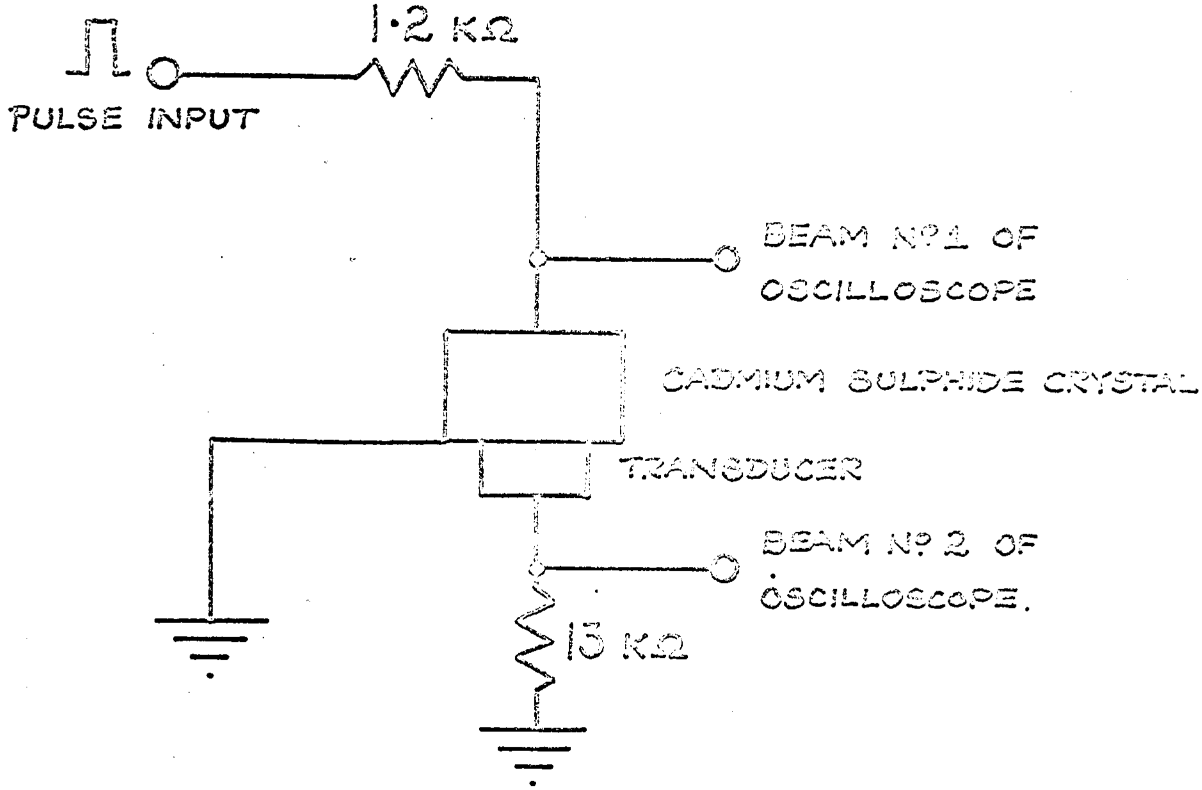

Fig. 2. Schematic of experimental set-up.

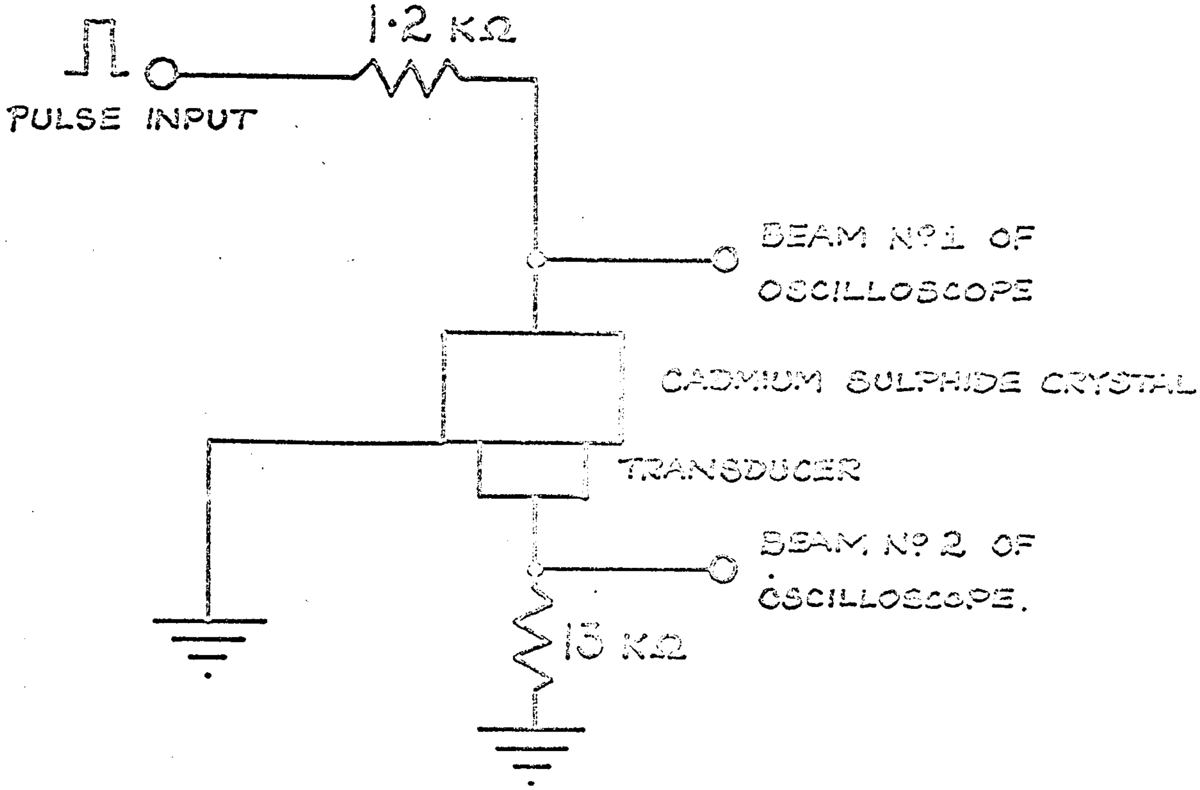

Fig. 2. SCHEMATIC OF EXPERIMENTAL SET-UP.

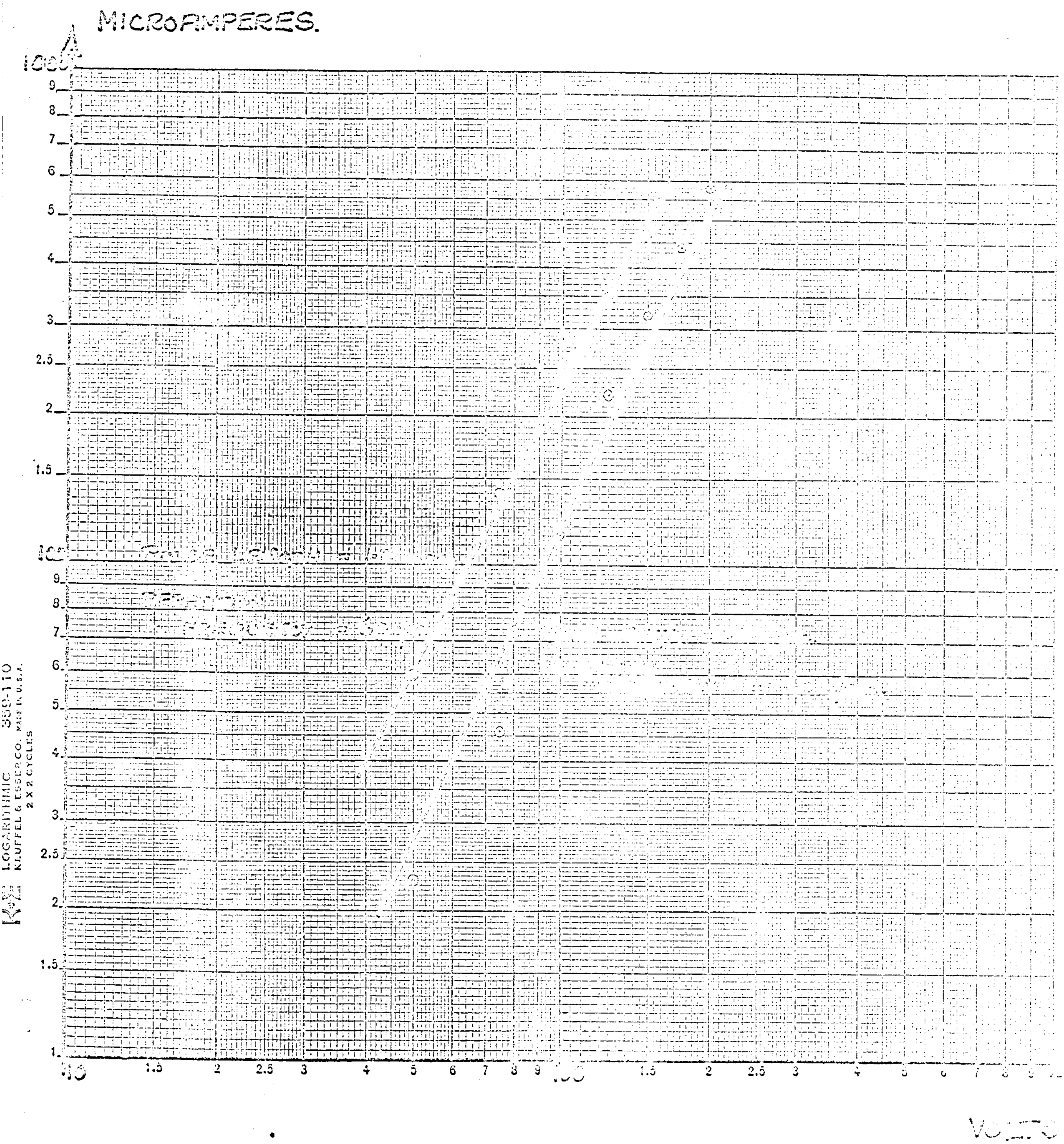

Fig. 4. CHARACTERISTICS OF THE FAILED CRYSTAL

SAMPLE MOUNT FOR CdS IMPEDANCE MEASUREMENTS. FIG. 5