AEROSPACE RESEARCH CENTER · GENERAL PRECISION SYSTEMS INC.

MATERIALS DEPARTMENT

BEAM ALIGNMENT TECHNIQUES BASED ON THE CURRENT MULTIPLICATION EFFECT IN PHOTOCONDUCTORS

by

Dr. Frank V. Allan, Dr. Robert Carvalho, Dr. Cecil B. Ellis
Dr. Aryeh H. Samuel, Mr. Joseph Scanlon and Dr. Daniel Grafstein

THIRD SUMMARY TECHNICAL PROGRESS REPORT

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Submitted by: C. B. Ellis
Dr. Cecil B. Ellis,
Senior Staff Scientist
Head, Physical Chemistry Section

Approved: Daniel Grafstein
Dr. Daniel Grafstein
Principal Staff Scientist
Manager, Materials Department

ABSTRACT

The photoconductive enhancement effect is the increase in photocurrent when two light spots are brought into coincidence on opposite sides of a thin photoconductor. The effect was discovered in doped CdS photoconductors using visible light, and has been previously investigated experimentally and theoretically under this contract.

This report covers the period 15 November 1966 to 15 October 1967 and describes the extension of the research program to an investigation of infrared sensitive photoconductors.

The experimental work was concerned with the development of the techniques required for infrared work. An A.C. detection method was developed and utilized in coincident beam experiments with mechanically lapped, single crystal germanium samples. In one experiment there was some evidence of the enhancement effect, but this result was inconclusive. Problems with electrical contact to the germanium surface led to the development of a new method for applying semi-transparent electrodes. It was found necessary to etch the germanium surfaces.

The theoretical model was applied to germanium and an enhancement effect was predicted for physically meaningful conditions.

An applications analysis was carried out. After further refinement, the results will be reported at a later date.

BETTY FELTER

ABSTRACT

A phenomenological study is made of the shock formation of tektites from a meteorite impacting on the earth. The calculation shows that if the meteorite that caused the Ries Kessel crater ejected large fragments from the parent meteorite at speeds of ~30 km/sec, these particles would interact with the terrestrial ejecta at the start of the recoil trajectory. A hypersonic ablation calculation at 20 km/sec is made for a single large fragment by extrapolating Hoshizaki's model for the heat transfer rate at an axisymmetric stagnation point.

The results of these calculations show that this physical model can yield the size and distribution of the tektite field being considered and also account for many of the various tektite characteristics. The analysis in this paper is limited to only observations, thus all refinements which do not clarify the basic physical model have been ignored.

INTRODUCTION

The purpose of this paper is to examine a physical model based upon a shock wave structure in order to explain the terrestrial origin of tektites found in the immediate vicinity of craters. Tektites in the Czechoslovanian field (moldavites) are considered in particular and with emphasis on their origin at the time of the Ries Kessel event.

A preliminary analysis of the propagation of high intensity wave discontinuities in impacting solids is currently underway. In order to reduce the problem to its essential physical characteristics an idealized model was chosen and will be discussed in a later communication. In this paper we wish to apply only the physical results as hypotheses to ascertain the relevance of that model to the facts of meteorites at hand.

A crystalline solid may be stressed into the plastic zone or beyond by the inertial reaction to a severe impact (Short, N.M., 1966, J. Geo. Educ., XIV, 4, 149). A shock wave then propagates through the material causing severe local supraplastic deformations, altering the chemistry along its path until it reaches the boundary of the material. At this point reflection and a transfer of momentum occurs which will lead to a high velocity mass ejection from the free surface of the solid, provided that this momentum transfer is above the rupture strength and response time of the solid. The directional energy of the shock wave is then converted to directional energy of the ejected fragment, thus little shock wave heating occurs to the matter that has been dislocated.

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III. INTRODUCTION AND DESCRIPTION OF PAST WORK

The investigation of the photoconductive enhancement effect has continued at General Precision Systems Inc. This is an Interim Technical Progress Report, prepared under the subject contract for NASA, the sponsoring agency. The report covers the period 15 November 1966 to 15 October 1967. The work was under the overall supervision of Dr. Daniel Grafstein, Manager, Materials Department, Aerospace Research Center. Participants included Dr. Frank V. Allan, Dr. Robert Carvalho, Dr. Cecil B. Ellis, Dr. Aryeh H. Samuel, and Mr. Joseph C. Scanlon. Dr. Allan is the Principal Investigator. The Contract Technical Director for NASA Electronics Research Center, EO/Space Optics Laboratory was Mr. Janis Bebris. As an introduction to the report on the work of this year, the early contract research up to October 1966 will first be summarized.

A. NATURE OF THE ENHANCEMENT EFFECT

The effect may be described in brief as follows: For a sandwich configuration cell, in which a thin sheet of photoconductor is contacted on each side by a thin, transparent electrode, it is possible to bring a beam of light to bear on either surface. In each case, granted the prerequisite of an external power supply, a photocurrent (i_1 or i_2) will flow. Under certain constraining conditions, collinearity of these beams in a so-called coincidence experiment results in a photocurrent (i_T) much enhanced in comparison with that which flows when the two beams are not aligned (i.e., i_1+i_2). The ratio of the former to the latter defines the magnitude of the enhancement factor (M):

$$M = \frac{i_T}{i_1+i_2} \qquad (3\text{-}1)$$

This effect is of interest due to potential applications for navigation and communications in space. Under this general heading may be grouped various possibilities. Tracking and alignment of a receiving station (space vehicle) may be undertaken by a sender which may be either earth-based, or possibly on another space platform. Once this is accomplished, conceivably the same link could be used for conveying telemetry, voice, or picture information between stations.

B. MATERIALS USED

Initial work was performed upon cells of cadmium sulfide (CdS), following the discovery of the novel enhancement effect in such materials. Cells were made of polycrystalline copper-doped CdS, with one electrode of transparent tin oxide backed by glass. Contact was made to the other face by a semitransparent film of indium or gold. The film thicknesses were in the range of 50 to 75 microns.

C. EXPERIMENTAL DEFINITION OF SOME OF THE GOVERNING PARAMETERS

Since two beams are necessary for the observation of the effect, it is obvious that many combinations of experimental parameters are possible. One immediate question is how different wavelengths of light compare in their efficacy for producing the enhancement.

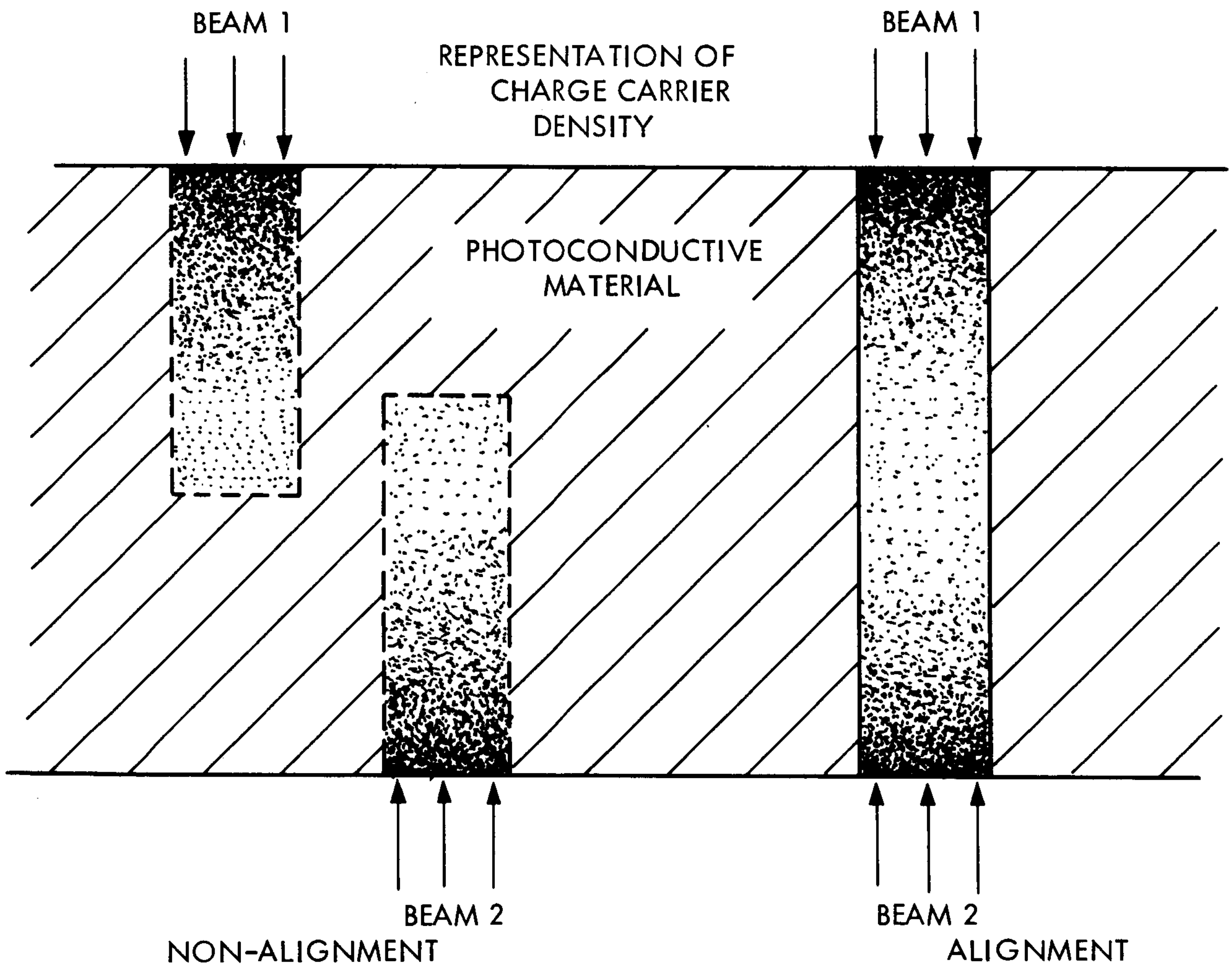
A survey of the wavelength dependence of the effect indicated that the value of M was usually a maximum when the wavelength of the beam falling on one side of the cell was in the region 520 to 530 μ. This is near the center of the band edge for pure CdS (510 mμ); although it was observed that the cells showed negligible photoconductivity with non-aligned beams in this region. Normally the greatest effect was observed when the wavelength incident on the other cell face was about 664 mμ. This corresponds to the maximum in the regular photoconductivity curve of the material, due to the copper impurity level in the band gap. However, the behavior from cell to cell was not completely consistent, since the greatest effect of M=1070 was observed when the wavelengths were both in the region of 510 to 540 mμ, where normal photoconductivity is only minimal.

A reasonable physical interpretation of the enhancement effect would be that the effect of each beam is to produce a certain concentration, and distribution in depth, of charge carriers; if these concentrations happen to overlap in the bulk of the cell, then conductivity will be favored greatly. Such a situation is sketched schematically in Figure 3-1.

Since it is apparent that other parameters than wavelength might affect the magnitude of M, several other aspects were investigated in detail. By conducting experiments with accurately calibrated lamps and filters, it was found that the effect was optimum for a particularly small power incident on each surface - about 0.7μW cm^{-2}, in the wavelength range of 500 to 550 mμ.

This may be related to the idea of producing an optimum carrier concentration profile within the specimen. At the lower power limit, the effect of irradiation would be swamped by noise current, whereas towards the other end of the scale, too great a light intensity on any one side would cause saturated photoconductivity. In this case the effect of bilateral illumination would be vitiated.

Another parameter studied was the strength of the electric field used. The result of observation of the effect of the electric field was surprising.



REPRESENTATION OF THE ENHANCEMENT EFFECT

FIGURE 3-1

It was found that M decreased with increasing field, falling asymptotically toward values only somewhat greater than unity. It is presumed that the same majority carrier type was produced by illumination at each side of the cell. Then, an electric field must impose an asymmetry on the system, since carriers will move toward one electrode and away from the other, disturbing their field-free distribution. Obviously this effect will be greater for larger fields. It seems that this effect might affect the conductivity adversely, resulting in a lower value of i_T and, hence, of M. This can be understood in terms of the depletion of charge carriers from the cathode region, thus increasing its resistivity and so defeating the condition illustrated in Figure 3 - 1. In the explanation of still another parameter, experiments showed that the magnitude of the enhancement effect was dependent upon the size of the light spot, or perhaps on the size of the light spot in comparison with the thickness of the CdS. Complete illumination of cell faces produced no enhancement (M=1). Tests in several cases showed that the optimum spot had a radius approximately the same as the cell thickness (50 to 75u) .

In another series of experiments, relative displacement of light spots from collinearity showed that M was related directly and indeed was often roughly proportional to the amount of overlap of the spots. This property could be important for use with tracking equipment. In an additional set of measurements it was found that the magnitude of M was not further increased if more than one pair of collinear spots was employed simultaneously. The effect of this finding upon the possibilities for pattern recognition applications was also analyzed.

D. CONSTRUCTION OF A DEMONSTRATION TRACKER

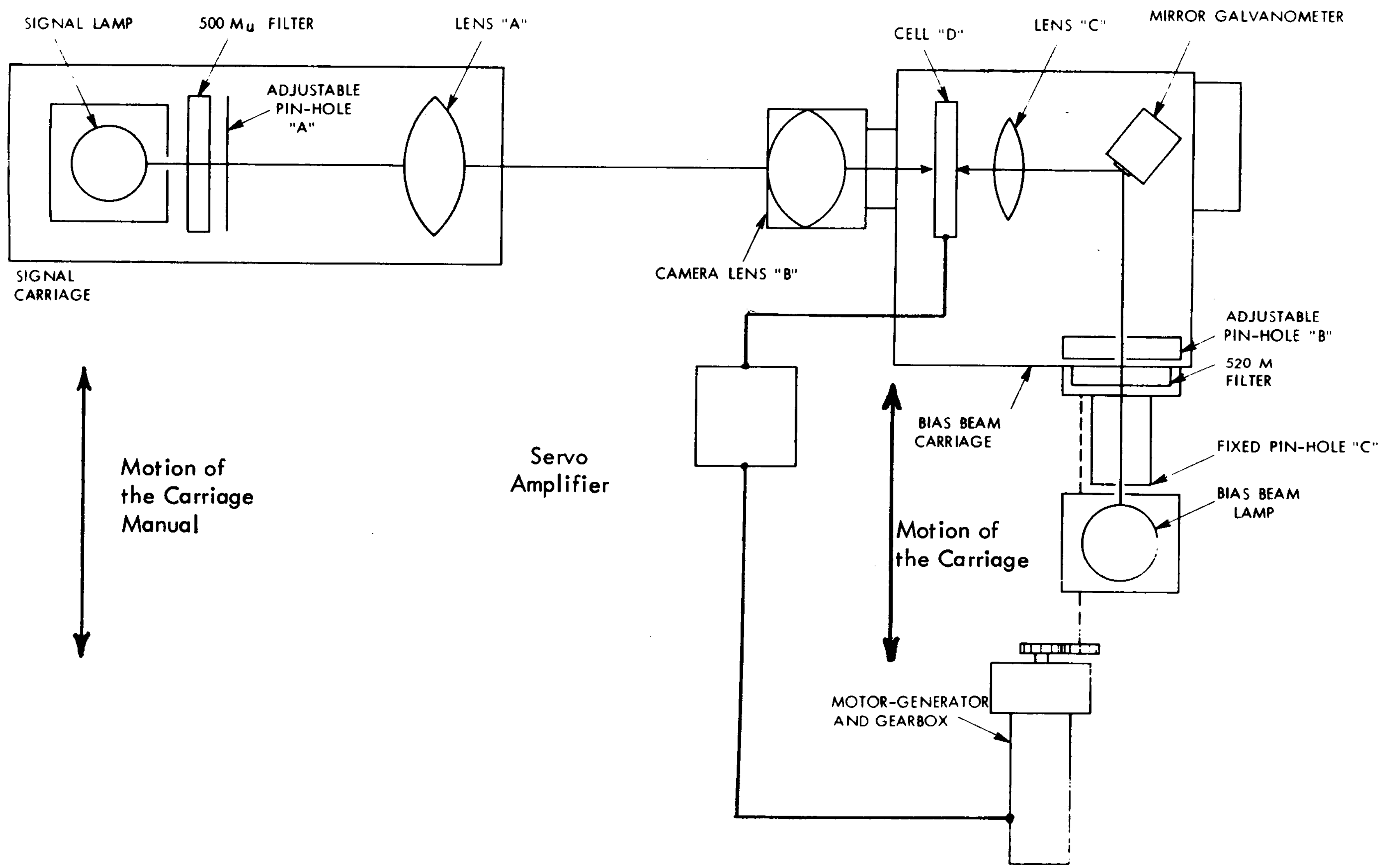
Once the experimental parameters were delineated,it was decided that a practical demonstration of the effect should be investigated. To this end, a beam follower device was designed and assembled as a breadboard. This consists of two parallel carriages, one carrying the source of a monochromatic light beam. It could be translated manually in a direction normal to the beam axis (Figure 1-4). The other carriage carries a CdS cell onto which an oscillating spot of monochromatic light from another source is focussed via a vibrating mirror. The light from the first source is focussed on the opposite side of the cell. As the light spot oscillates across the cell-face, an output signal is derived from the cell. If the two spots coincide at all, an enhanced signal is generated. Non-collinearity of the light beams will produce an asymmetric(or error) signal. This is amplified and used to operate a motor, phased to drive the second carriage to the position of minimum error signal. Thus, one carriage is made to follow the other. This demonstration device operated satisfactorily tracking at a speed limited by the 2 cps frequency used for the vibrating mirror. This schematic arrangement is shown in Figure 3-2.

E. MATHEMATICAL MODEL OF THE ENHANCEMENT PHENOMENON

As a guide to the research, a mathematical model of the behavior of the photoconducting material was generated in order to try to explain the effect. Due to complexities of the real situation, this was limited to a one dimensional model in which the charge carrier concentration within the cell,in the direction of the light beams only,was considered. This model was based upon consideration of a steady state kinetic expression in which the dynamic balance of charge carriers (electrons)

FIGURE 3-2

BREADBOARD BEAM FOLLOWER DEVICE



is considered. They are generated by absorption of the light in accord with the Lambert-Beer law, and their eventual fates are to recombine with holes either directly, or more probably, via trapping states. The effects of thermal and electric field diffusion during their free life are included in the model.

The general case of this model involves ten parameters, of which only three are under experimental control: these are the intensities of the beams and the cell thickness. The seven remaining are material parameters, which are ill defined for doped polycrystalline materials.

Three computer programs were written and used with the IBM 7040 computer to calculate possible values of M in a systematic manner.

The first program, ONESTEP, enabled a single parameter to be varied stepwise for a predetermined number of steps. Although this was able to predict a value of M as high as 5.73, it was felt that a more powerful method was needed. As a result, the SEARCH program was evolved. In this, all the parameters were varied in a stepwise mode, in a predetermined sequence. The program was written so that only steps leading to larger values of M were made. In this way, maximum values of M were sought and the ONESTEP program was rendered redundant. M values as high as 5×10^8 were computed.

Once regions of high M were located, it was desired to compute the dependence of M on each parameter in such a region. For this purpose a new, more powerful program, ALLSTEP, was written. This had the capability to compute dependence of M on all parameters with just a single input.

By judicious choice of parameters, it was found possible for the model to yield values of M in agreement with experiment. However, the usefulness of the model was crippled severely by the uncertainties in the chosen material parameters. Small changes in some of these may alter M drastically, as was indicated by the results of the computations.

F. INITIATION OF GERMANIUM RESEARCH

Certain photoconductors, particularly intrinsic germanium (Ge) and silicon (Si) are known to have well defined material parameters in the monocrystalline state. If the enhancement effect could be obtained in these crystals, the phenomenon should be considerably easier to understand and control. The mathematical model should be of more assistance in such a case.

Also, these materials are photosensitive in the infrared, which is a spectral region of special interest for a number of applications, such as tracking the edge of a planet from a space vehicle.

For such reasons, it was decided to leave the work on polycrystalline CdS in abeyance, in order to concentrate effort upon single crystals of Ge and Si.

G. AIMS FOR THE PRESENT REPORT PERIOD

The continuation of work under Contract NAS 12-8 since October 1966, which is reported in the body of this report, had three main aims.

1. Detection of the enhancement effect in single crystal germanium.
2. Adaptation of the mathematical model to such germanium to see if a prediction could be made as to the degree of

enhancement which should be expected in this material.

3. A detailed scientific and engineering survey of possible applications for the enhancement phenomenon, with an analysis of the probable competitive advantages of devices using this effect, in comparison with other kinds of sensors. This work will be reported at a future date.

The next chapter describes the experimental work on Ge carried out during the year just concluded.

IV. EXPERIMENTAL RESULTS

In this chapter we present the experimental methods used, and the results obtained, in our investigation of intrinsic germanium.

First, an explanation is presented of the necessity for a different experimental technique for single crystal Ge than was used with polycrystalline CdS. This is followed by descriptions of the apparatus and the material samples. Then the quantitative results of the experiments are presented. It will be shown that the enhancement effect has not yet been observed in Ge, with the possible exception of one experiment in which the noise level made the result uncertain. Finally, the possible causes of the failure to observe the enhancement effect to date are considered , and an account is given of new experiments which are intended to circumvent some of the known limitations of the earlier experiments.

A. A.C. DETECTION OF PHOTOCONDUCTION IN GERMANIUM

As photoconductors, Ge and CdS have quite different properties. Ge has a much lower specific resistance (ρ) at room temperature than CdS; ρ for intrinsic Ge is about 40 ohm-cm[1] while ρ for the CdS used in our coincidence cells is of the order of 10^9 ohm-cm. In addition, the change in resistance upon irradiating is much greater in CdS than in Ge - several orders of magnitude greater. Thus, for the bias voltage required to yield measurable photosignals in Ge much larger bias currents will flow than is the case with CdS.

Furthermore Ge has its peak photoresponse in the infrared, at about $1.4\,\mu$[2]. The detectivity (D^*_λ) value for Ge at this wavelength is about 100 times less than the peak D_λ^* value for CdS. Thus, for comparable photosignals Ge will require higher intensity radiation than CdS. Also, because of germanium's relatively narrow forbidden gap, it has a relatively large temperature coefficient of resistivity, so small temperature changes due to the thermal effect of the incident radiation cause a noticeable change in resistance of Ge. This is thermal drift, which does not occur in CdS.

Because of these differences, the study of photoconductivity in Ge requires somewhat different methods than were used in the CdS studies. The thermal drift and high bias currents make it impractical to attempt measurements of D.C. photocurrents. Chopped light is used to generate a periodic signal which is susceptible to A.C. detection; in this way the troublesome D.C. bias current is discriminated. However, it is not easy to measure periodic photocurrents at the low levels (nanoamperes) which are produced. Therefore the photosignals are observed by measuring the A.C. voltage across a resistor in series with the photoconductor.

B. EXPERIMENTAL REQUIREMENTS

The essential elements of a coincident beam experiment are 1) a sample which is mounted in a suitable holder, 2) an electrical circuit which includes a power source for biasing the sample and a series load resistor, 3) two beams which are directed to opposite faces of the sample, and 4) a sensitive microvoltmeter for measuring the photosignals.

Figure 4-1 shows an exploded view of the sample holder and Figure 4-2 shows how a Ge disc fits into the holder between discs of conducting glass. Electrical contact is made between the cover and the surface of the Ge through the conducting glass and the brass retaining rings. Electric leads attached to the screw terminals connect the sample holder with the rest of the circuit.

A schematic diagram of the electrical circuit is given in Figure 4-3. In most experiments a 1.5 volt dry cell was used as the power source. The load resistor was chosen

FIGURE 4-1

EXPLODED VIEW OF SAMPLE HOLDER

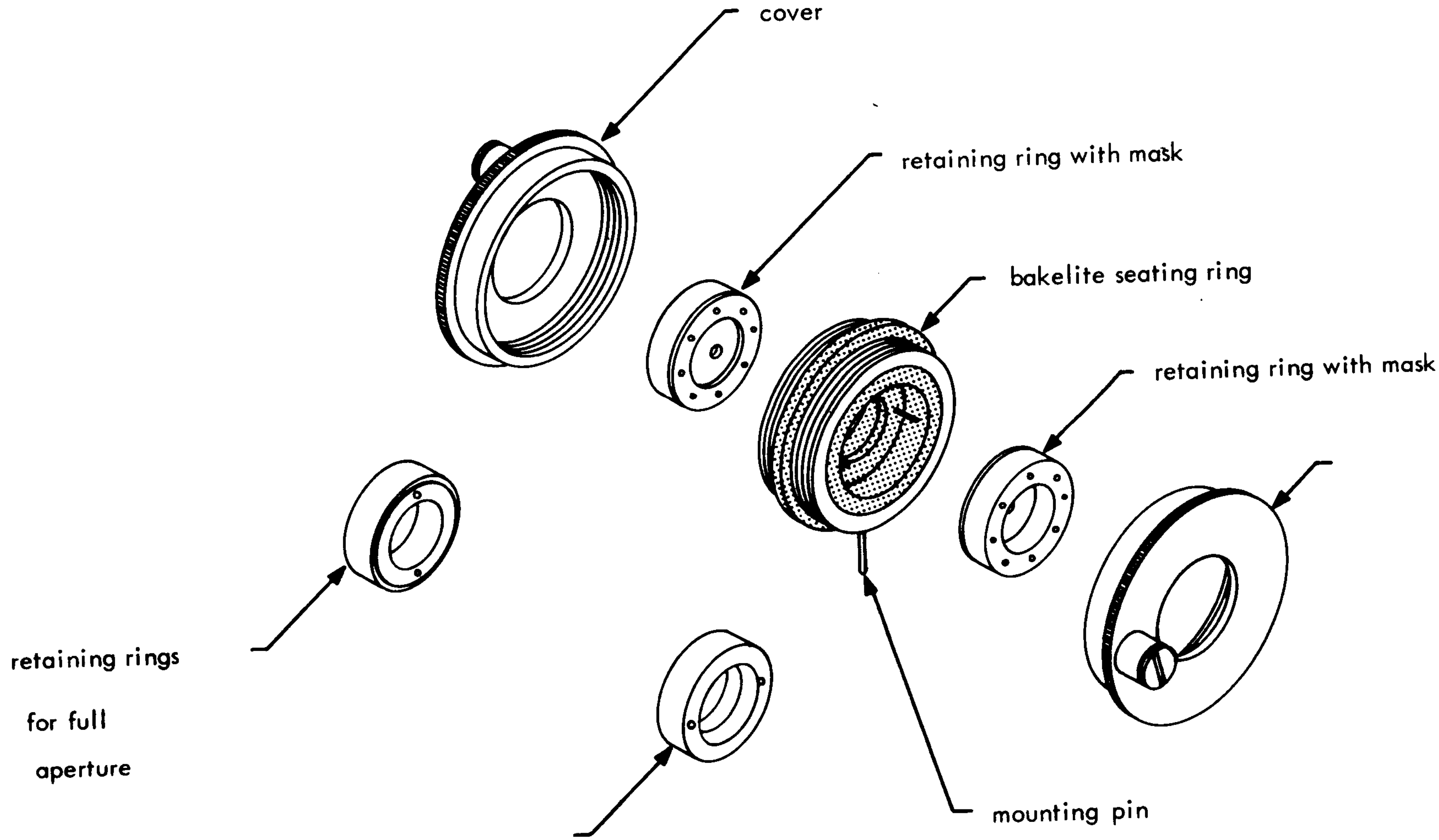
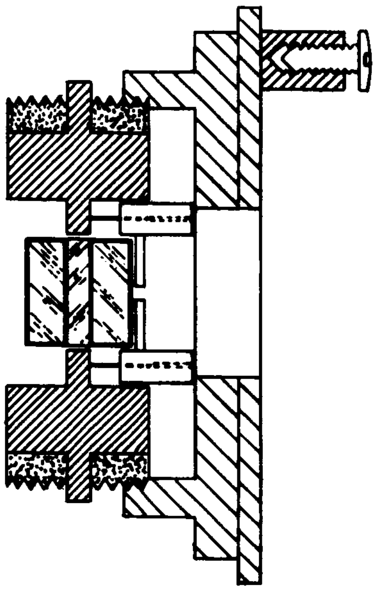


FIGURE 4-2

SECTION VIEW OF SAMPLE HOLDER



DETAIL

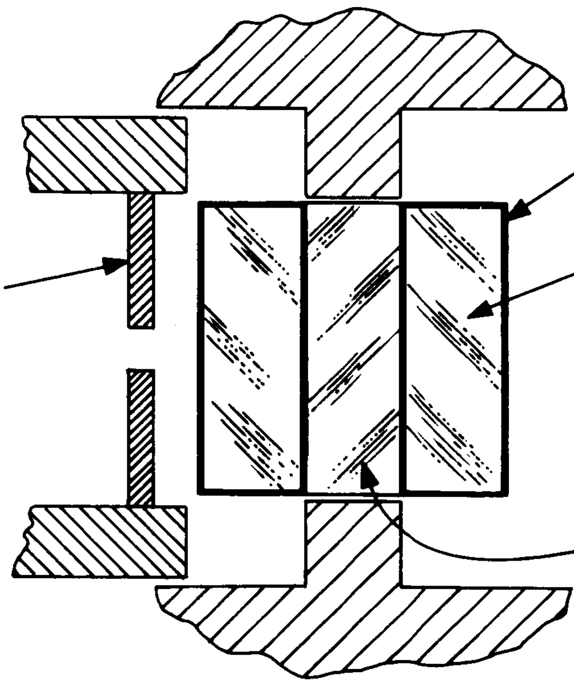
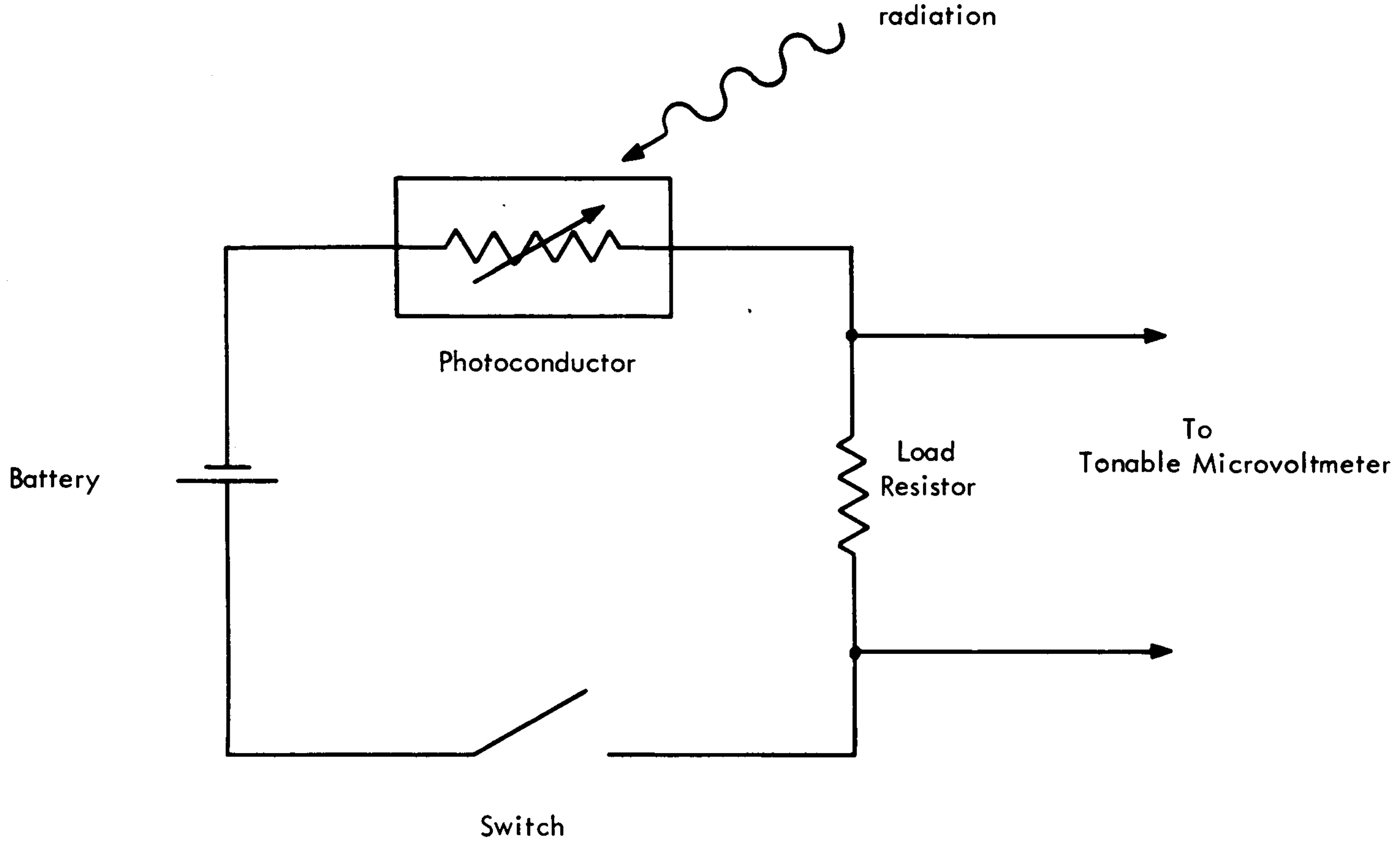


FIGURE 4-3

SCHEMATIC DIAGRAM OF ELECTRICAL CIRCUIT



to be approximately equal to the measured resistance of the Ge. The battery and load resistor are encased in an aluminum box. All inter-connections outside the box are made with shielded cable.

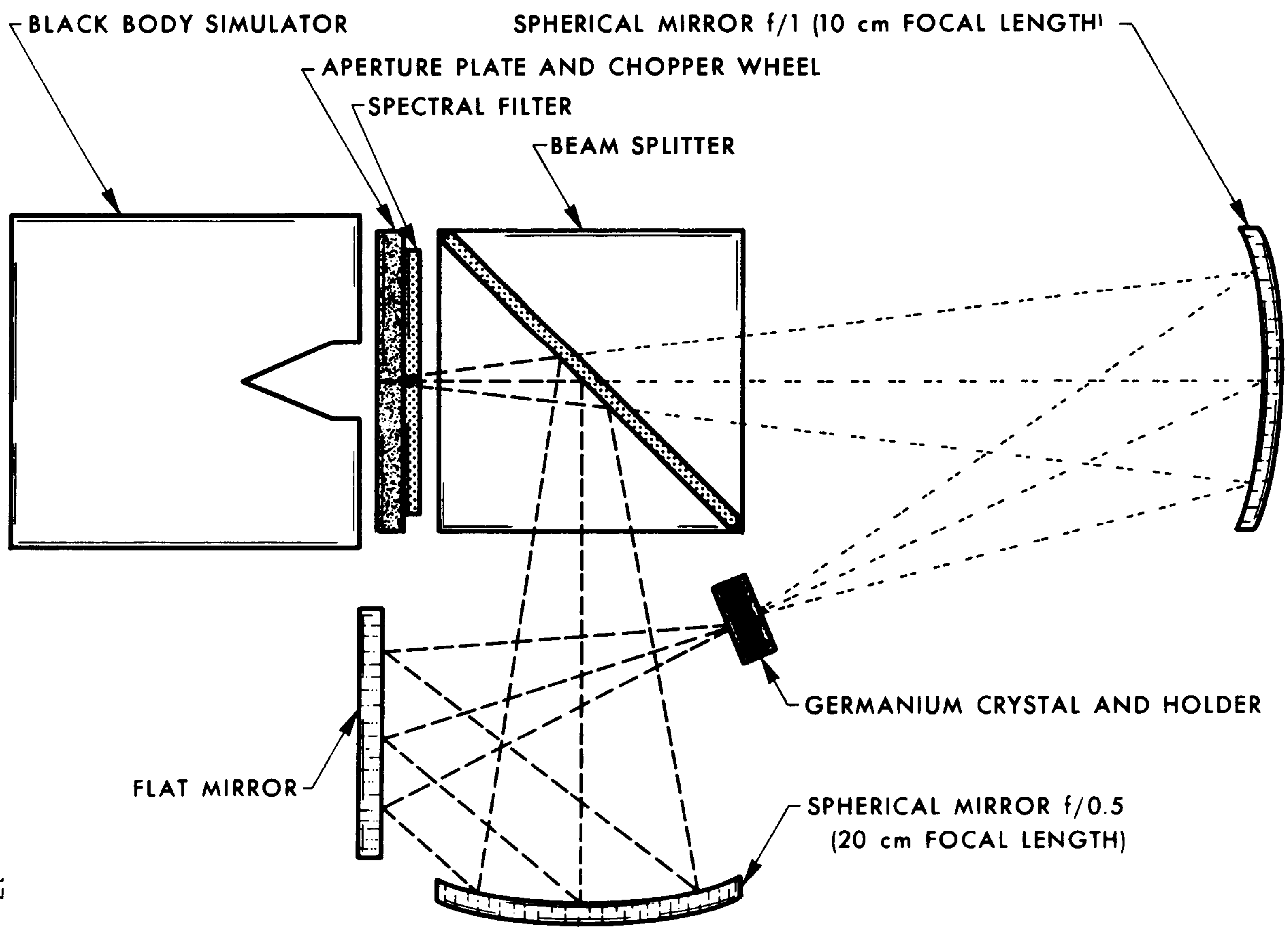
To produce a radiation beam, a radiation source and the optical components necessary to bring the beam to bear on the sample are required. Furthermore, interference filters -- for wavelength selection, and, possibly, neutral density filters -- are used to produce monochromatic beams of the desired intensity. Experiments were done with a number of optical configurations; Figure 4-4 illustrates the arrangement that was used in the most recent experiments. With this set-up a single radiation source is used to produce the two beams through the use of an optical beam splitter. The source shown in the figure is a blackbody simulator Infrared Reference Source, Model 11-200T (Barnes Engineering Company). It provides adjustable blackbody radiation over the temperature range 200 to 1000 degrees centigrade. The simulator is calibrated in terms of the blackbody radiance; from this value, and a knowledge of the parameters of the optical system, the spectral irradiance at the sample can be calculated. For experiments, requiring a higher radiant intensity, a 150 watt quartz-bromine tungsten lamp was substituted. The quartz-bromine lamp which operates at a color temperature of $3400^{\circ}K$ was calibrated in terms of its blackbody intensity by means of an Eppley thermopile. Either source is provided with a variable aperture plate and a two-speed (15 and 90 cps) mechanical chopper. The source and chopper are both mounted on the base of the aperture plate. In some experiments two independent blackbody simulators (with their associated aperture plates and choppers) were used to produce the two beams; with this arrangement the beam splitter and mirrors were not used.

For measurement of the periodic signals a Tunable Microvoltmeter (TMV) Model 600 (Infrared Industries, Inc.) was used. This instrument measures rms voltages.

FIGURE 4-4

ENHANCEMENT EFFECT EXPERIMENT

RADIATION FOCUSSING WITH SPHERICAL MIRRORS



In our experiments the TMV is tuned to the chopping frequency. The detection bandwidth can be adjusted independently to a minimum half-width of 4 percent (at - 3 dB). In most experiments the minimum bandwidth was used. The maximum sensitivity of the TMV is 0.01 microvolt full scale.

C. MATERIALS

Single crystal Ge discs, 1 cm in diameter, were obtained from Semi-Elements, Inc. The supplier stated that the minimum resistivity of the crystal from which the discs were cut was 40 ohm-cm as measured by a four point probe, corresponding to 99.99999 percent purity.

Discs were obtained in two different crystallographic orientations -- with the faces of the disc parallel to either the 100 crystal plane ("the 100 samples") or the 111 crystal plane ("the 111 samples"). For each orientation, five discs were obtained; three discs are 1 mm thick, one is 2 mm, and one is 3 mm thick. A total of ten discs was obtained. All discs had mechanically lapped surfaces.

For purposes of identification, the 1 mm thick discs were given the following designations. The 100 samples -- Ge 1, Ge 2, and Ge 3. The 111 samples -- Ge 4, Ge 5, and Ge 6. No special designation was applied to the thicker discs.

D. MEASUREMENTS

1. Definition of Enhancement Factor

A coincident beam experiment requires at least four measurements: the dark signal, i.e., the TMV reading when no radiation is falling on the photoconductor (V_D); the signals obtained with single side irradiation (V_1 and V_2); the signal obtained with the beams in coincidence (V_T). The enhancement factor M has previously been defined in terms of currents. By analogy, we define the enhancement factor in terms of the voltage drop across a series load resistor as

$$M = \frac{V_T - V_D}{(V_1 - V_D) + (V_2 - V_D)} \qquad (4\text{-}1)$$

The signals, it will be recalled, are measured with an A.C. microvoltmeter and are rms values. The maximum uncertainty in any measurement was found to be $\pm 0.5 \mu V$. An experiment may be further described by specifying the following conditions.

a) The identity of the sample
b) The wavelengths of the incident radiation beams
c) The size of the spots on the sample
d) The irradiance (Watts/cm^2) of the sample
e) The chopping rate
f) The applied voltage (across the germanium-plus-load resistor)
g) The resistance of the sample

Before each series of experiments the resistance of the germanium sample was measured. For maximum sensitivity, the load resistance would be made equal to the dark resistance of the sample.

2. Preliminary Measurements

a. Resistance of Germanium Samples

In order to determine the approximate value of the load resistor, the resistance of each of the samples cut to the 100 face was measured. Measurements were made by sandwiching the discs between plates of conducting glass and then touching the probes of an ohmmeter to the conducting glass surfaces. For the five samples the resistances measured in this way varied from 50 to 300 ohms. (In subsequent experiments the resistances were found to have increased, see below.) There was no systematic change with thickness. However, the resistances were somewhat dependent on the pressure exerted on the sandwich. When the resistances were measured with the samples sandwiched between conducting glass in the sample holder, similar high and variable resistances were obtained.

These measured values running to more than 50 ohms are considerably higher than the values that are calculated from the resistivity (ρ) of germanium. For ρ = 40 ohm-cm, a 0.1 cm thick disc, 1 cm in diameter should have a resistance across the faces of 5 ohms. If our germanium samples are unusually pure and "perfect" crystals, the resistance should be no more than about 10 ohms.

The anomalously high resistance was attributed to the contact between the conducting glass and the germanium surface. However, it was found that photoconductivity could be observed, at the expected level, despite the high resistance. It was therefore decided that a search for the enhancement effect would be pursued; if an enhancement effect were not found, then we would return to a consideration of this high resistance.

b. Chopping Modes

In a coincidence experiment using A.C. detection, three modes of modulation are distinguishable.

(1) Each beam is chopped independently (independently chopped mode)

(2) One beam is chopped while the other is not chopped (chopped/steady mode)

(3) Both beams are chopped in-phase (in-phase mode).

A number of experiments was carried out in the independently chopped mode. In every experiment it was found that V_T fluctuated periodically -- the period being approximately one cps. Presumably, this periodic behavior results from a slight difference in the two chopping frequencies (both nominally 90 cps) which gives rise to a low frequency "beat". When the maximum value of V_T was used in Equation 4-1, the value of M was calculated to be less than 1. This apparent decrease is thought to be associated with the slow response of the meter and is therefore not considered significant.

With the chopped/steady mode, the steady beam gives no photosignal for single side illumination since a steady beam does not produce an A.C. signal. If the chopped beam gives a photosignal of V_1 for single side illumination and the steady beam gives $V_2 = V_D$, then the expression for the enhancement factor becomes

$$M = \frac{V_T - V_D}{V_1 - V_D} \qquad (4\text{-}2)$$

Several experiments were carried out in this mode. In no case was a value of M greater than 1 observed. However, in some experiments where polychromatic radiation was used, the enhancement factor was found to be less than 1. M values as low as 0.85 were obtained. These fractional values of M appear to be associated with high radiation intensities and therefore they may result from saturation of the photosignal.

The in-phase mode is established when one source and one chopper are used with an optical beam splitter. This system has been previously described (Figure 4-4). All experiments reported in sections 3 and 4 below were carried out in the in-phase mode at a chopping frequency of 90 cps.

3. Search for the Enhancement Effect

a. Using Polychromatic Radiation

The first experiments with coincident radiation were carried out with unfiltered black body radiation. Tables 4-1 through 4-5 summarize the results.(All irradiance values have uncertainties of $\pm$ 50 percent). Tables 4-1 through 4-4 give the M values for full surface irradiation at four different levels of irradiance. Table 4-5 gives the result for coincident spots of 0.3 cm radius. In all of these experiments the value of the enhancement factor was not significantly different from 1.

b. Using Monochromatic Radiation

By placing a narrow band pass interference filter between the radiation source and the optical beam splitter, monochromatic beams irradiate each side of the sample. A set of filters were used which have half-widths at half-maximum of approximately 30 mμ; the $\lambda_{max.}$ were spaced at intervals of 100 mμ. These filters transmit about 1 percent of the total power emitted by a black body at 1000°C; therefore the photosignal generated with the filtered radiation is considerably less than with unfiltered radiation.

Table 4-6 gives the results of a series of experiments with monochromatic beams. It can be seen that, in all but one case, the enhancement factor is virtually 1. However, where the wavelength is 1.3 μ, M is measured as 4. The principal source of error in this measurement is random noise fluctuation in the signals. Because of the small signal levels in this case, the fluctuation was 20 to 50 percent of the signal. This is sufficient to cast considerable doubt on the measured value of M. An attempt was made to correlate a value for the enhancement factor using the theoretical expression (equation 5-1). The calculation is described in Chapter V.

TABLE 4 - 1

Coincidence Experiment with Polychromatic Radiation

Sample Ge 1

λ : polychromatic, both beams

Spot Size: full surface, $A = 0.4\ cm^2$

Irradiance: $I_1 = 0.04\ mW/cm^2$; $I_2 = 0.12\ mW/cm^2$

Chopping Rate: 90 cps

Applied Voltage: 1.5 V

Sample Resistance: 480 Ω

Signals (μ v)

$V_D = 0.6$

$V_1 = 4.1$

$V_2 = 13.0$ M = 1.1

$V_T = 17.5$

Repeat $V_D = 0.6$

$V_1 = 4.3$ M = 1.0

$V_2 = 13.6$

$V_T = 17.5$

TABLE 4 - 2

Coincidence Experiment with Polychromatic Radiation

Sample Ge 1

λ : polychromatic, both beams

Spot Size: full surface, $A = 0.4\ cm^2$

Irradiance: $I_1 = 0.01\ mW/cm^2$; $I_2 = 0.03\ mW/cm^2$

Chopping Rate : 90 cps

Applied Voltage: 1.5V

Sample Resistance: 480Ω

Signals (μ v)

$V_D = 1.8$

$V_1 = 12.1$

$V_2 = 34.0$ M = 0.96

$V_T = 42.5$

TABLE 4 -3

Coincidence Experiment with Polychromatic Radiation

Sample Ge 1

Conditions same as Table 4-2 except

Irradiance: $I_1 = 2$ m W/cm^2; $I_2 = 1$ m W/cm^2

Signals (μ v)

$V_D = 1$

$V_1 = 520$

$V_2 = 370$ M = 0.99

$V_T = 880$

TABLE 4- 4

Coincidence Experiment with Polychromatic Radiation

Sample Ge 1

Conditions same as in Table 4-2 except

Irradiance: $I_1 = 2.6$ mW/cm^2; $I_2 = 1.3$ mW/cm^2

Signals

$V_D = 1$

$V_1 = 380$

$V_2 = 270$

$V_T = 647$

M = 1.00

TABLE 4-5

Coincidence Experiment with Polychromatic Radiation

Sample Ge 4

λ : polychromatic, both beams

Spot size: $r = 0.3$ cm, $A = 0.33$ cm^2

Irradiance: $I_1 = 0.6$ mW/cm^2; $I_2 = 2$ mW/cm^2

Chopping rate: 90 cps

Applied voltage: 1.35 V

Sample Resistance: 620 Ω

Signals (μ V)

$V_D = 2$

$V_1 = 71$

$V_2 = 312$ $\qquad$ $M = 0.97$

$V_T = 360$

TABLE 4-6

Coincidence Experiments with Monochromatic Radiation

Sample Ge 1

λ : see below

Spot size : r = 0.3 cm, A = 0.33 cm^2

Irradiance: see below

Chopping Rate: 90 cps

Applied Voltage: 1.5 V

Sample Resistance: 480 Ω

V_D = 1.0 μ V

$\lambda^*_{max}(\mu)$	I_1 (mW/cm^2)	I_2 (mW/cm^2)	$V_1(\mu V)$	$V_2(\mu V)$	$V_T(\mu V)$	M
1.3	.002	.001	1.3	0.9	2.3	4.3
1.4	.005	.003	4.0	1.8	5.5	1.2
1.5	.003	.002	3.3	1.6	---	---
1.6	.002	.001	6.0	4.0	9.8	1.1
1.7	.003	.002	16	12.5	28	1.0
1.8	.006	.003	26	19	44	1.0
1.9	.003	.001	10	12	22	1.0
2.0	.006	.003	4.0	3.0	6.5	1.1

* both beams

The experiment with 1.3μ radiation was repeated, but it was found that photoconductivity could no longer be detected under the same experimental conditions. Apparently the photosensitivity had decreased. A resistance measurement showed that the resistance of Ge 1 had increased to 1100 ohms. A check of Ge 2 and Ge 3 revealed that these samples also had increased in resistance -- to 8500 ohms and 750 ohms, respectively. The cause of this change in the sample properties with time has not been determined, but it presumably involves surface oxidation layers.

With the higher intensity quartz-bromine lamp used as a radiation source, additional coincident beam experiments were carried out. Table 4-7 gives the results for Ge 1. It shows that at 1.3 μ the sample has an enhancement factor of 1. However, the irradiance in this experiment is about ten times as great as in the experiment in which the value of M was 4. So we have not duplicated the conditions of the earlier experiment and, therefore, cannot definitely state that the earlier result was incorrect. The other wavelengths, i.e., 1.4 through 2.0 μ, did not yield a significant enhancement effect in Ge 1. The quartz-bromine lamp had sufficient radiant intensity so that a photoresponse could be measured at 1.7 μ with a spot radius of 0.03 cm but here too the enhancement factor was only 1.

Measurements of the photoresponse of Ge 2 and Ge 3 to polychromatic radiation indicated that monochromatic photosignals would be too weak to be measurable so no further experiments were made with those samples. Coincidence experiments were attempted with Ge 4. Only at 1.7 μ was there a measureable response. The M values appear in Table 4-8. Again we see that no trustworthy enhancement effect was observed.

4. Resistance and Noise

Having failed to measure a significant enhancement effect, a closer consideration of the anomalously high -- and increasing -- resistances of the germanium samples

TABLE 4-7

Coincidence Experiments with Monochromatic Radiation

Sample: Ge 1

λ : See below

Spot size : r = 0.3 cm, A = 0.33 cm^2

Irradiance: See below

Chopping Rate: 90 cps

Applied Voltage: 1.35 V

Sample Resistance: 1100 Ω

$V_D = 2\,\mu V$

$\lambda^*_{max}(\mu)$	$I_1(mW/cm^2)$	$I_2(mW/cm^2)$	$V_1(\mu V)$	$V_2(\mu V)$	$V_T(\mu V)$	M
1.3	0.024	.012	3	2.5	3.5	1
1.4	0.050	.025	5	3	8.5	1.6
1.5	.030	.015	4	3	6.5	1.5
1.6	.025	.013	23	17	39	1.0
1.7	.033	.016	42	30	68	1.0
1.8	.060	.030	50	29	77	1.0
1.9	.028	.014	30	15	44	1.0
2.0	.064	.032	9	5	13	1.1

For a smaller spot size: r = 0.1 cm, A = 0.033 cm^2

$\lambda^*_{max}(\mu)$	$I_1(mW/cm^2)$	$I_2(mW/cm^2)$	$V_1(\mu V)$	$V_2(\mu V)$	$V_T(\mu V)$	M
1.7	.033	.016	4	3.3	5.5	1.1

* both beams

TABLE 4-8

Coincidence Experiments with Monochromatic Radiation

Sample Ge 4

$\lambda : \lambda_{max} = 1.7\mu$ for both beams

Spot size: $r = 0.3$ cm, $A = 0.33$ cm^2

Irradiance: $I_1 = 0.016$ mW/cm^2 , $I_2 = 0.033$ mW/cm^2

Chopping Rate: 90 cps

Applied Voltage: 1.35 V

Sample Resistance: 620 Ω

Signals (μV)

$V_D = 2$

$V_1 = 3.3$

$V_2 = 22$ M = 1.0

$V_T = 24$

Repeat $V_D = 2$

$V_1 = 3$

$V_2 = 16$ M = 1.1

$V_T = 18$

was undertaken. Earlier, measurements of resistance for various contact systems inside the sample holder gave the results shown in Table 4-9. The first column shows the materials that were placed between the retaining rings to carry the current. It was thought that the noise, i.e., the dark signal, V_D, was associated with the resistance, so the noise was measured also. From these data we can see that the high resistance must be associated with the interface between the conducting glass and the germanium disc; both the conducting glass and the germanium make a contribution. However, we see from systems 7 and 8, that even with an indium coating a germanium disc still has too high a resistance. As for the noise, its virtual disappearance when the sample is shorted indicates that the source of the noise is the sample itself.

In an attempt to determine the noise mechanism, the frequency spectrum was measured by observing the noise voltage (V_D) over a range of detection frequencies (f). This is particularly easy to do with the TMV. The noise spectrum is plotted in Figure 4-5. The log of the noise voltage normalized to unit detection bandwidth, $V_D/\Delta f$, is plotted against log f ; log V_D is proportional to log $\bar{i}^2$. In the case of a current noise mechanism, the plot of $\bar{i}^2$ versus log f is linear.

It can be seen that our data do not give a linear plot. Therefore, it seems likely that the noise is not just current noise, but rather, it results from a combination of mechanisms.

5. Technique Considerations

The above mentioned experiences with fluctuations of the apparent sample resistance led to further measurements on this phenomenon. Two main causes of abnormal resistance were considered, namely the purity of the samples and the nature of the sample-to-electrode contacts. These technical considerations will be dealt with in sequence.

TABLE 4-9

Resistance and Noise of Various Contact Systems

System	Resistance (Ω)	Noise (μV)
1. R-G-Ge 1 -G-R	600	1-2
2. #1 shorted	< 1	<0.01
3. R-G-G-R	130	1.5
4. R-A-Ge 1-A-R	200	1
5. R-S-R	<1	0.01
6. R-G-Ge 2-G-R	8500	1
7. R-G-Ge 2*-G-R	500	1
8. R-W-Ge 2*-W-R	500	1

Code:

R = Retaining Ring in sample holder

G = Conducting glass

A = Aluminum foil

S - Copper spring

Ge 1, Ge 2 - Germanium disc samples

Ge 2* = Ge 2 with indium coatings on the faces

W = Brass washers

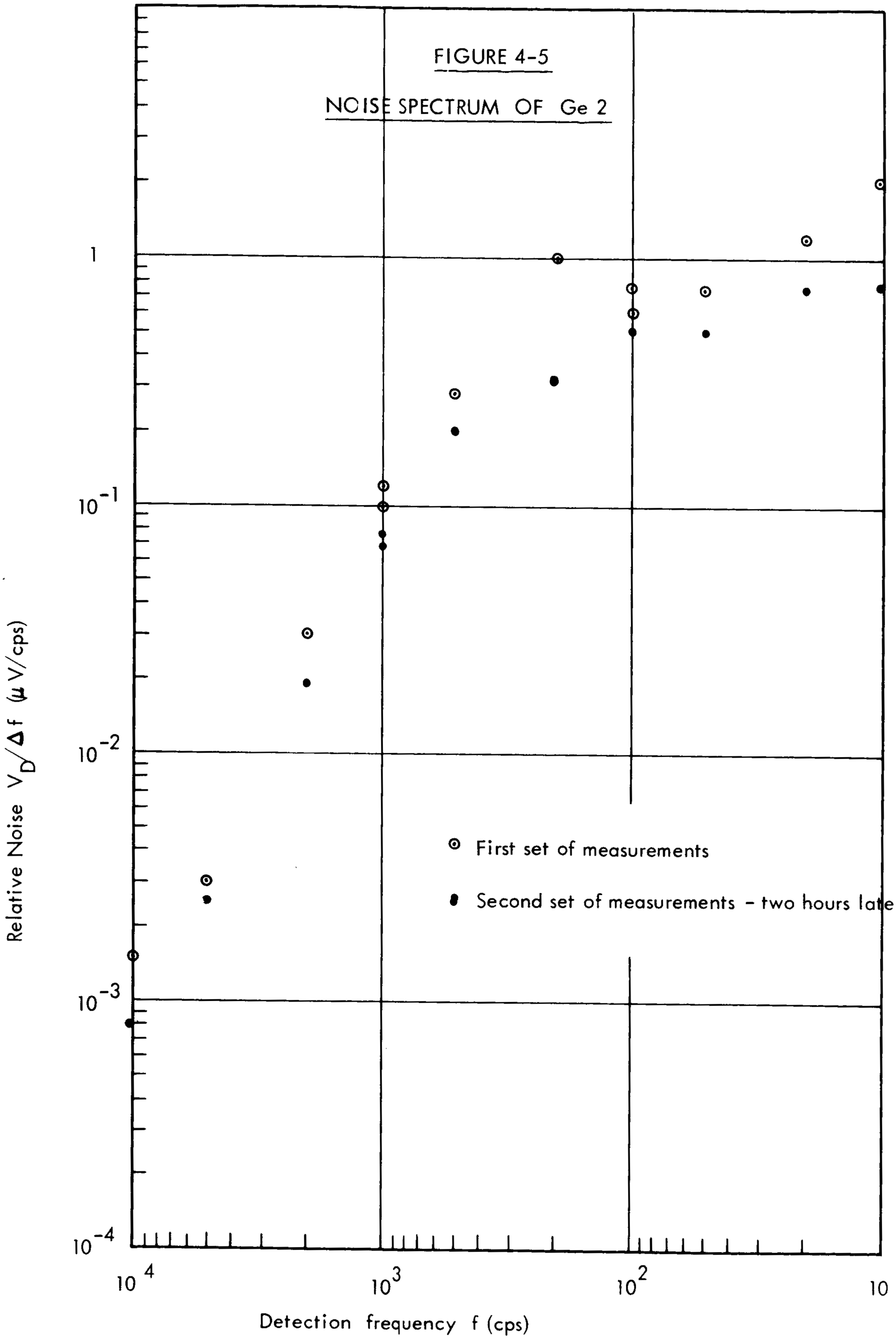


FIGURE 4-5
NOISE SPECTRUM OF Ge 2
First set of measurements
Second set of measurements - two hours later
Relative Noise $V_D/\Delta f$ (μV/cps)
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^4
10^3
10^2
10
Detection frequency f (cps)

a. Sample Properties

The germanium discs were cut by the suppliers from single crystal boules, stated to be of 99.99999 percent purity. The samples were studied spectroscopically in order to confirm this claim. An emission spectrogram was made using a small sample of the material with the largest size Jarrell Ash spectrograph . It was found that the only detectable impurity was silicon to the extent of less than 0.00001 percent. It is not thought that such an impurity, having the same valence as the host, should have a deleterious effect upon the electrical properties.

In order to study the infrared transmission spectrum, it was necessary first to clean the sample surfaces by etching. This process is detailed in the section on contacts.

From the infrared spectrum the absorption band edge was found to extend from 1.67 to 1.97 μ with the point of half intensity at the mean of these values, i.e., 1.82 μ. The best available literature value for the indirect band gap is that of McFarlane et al[3] who quote a value of 0.670 ev at 291^{o}K; this is equivalent to 1.85 μ. At this wavelength, our sample has attained 75 percent its transmission at 1.97 μ. It is not possible to derive an exact band edge value from such a transmission curve, but it would seem at least that the specimen had properties corresponding closely to those of pure germanium. The normal test of purity for semiconductors such as germanium is the measure of electrical resistivity, since this property is very sensitive to impurities, especially those of valence other than four. Measurements with a simple four point probe, which eliminates contact difficulties, yielded a value of 70 ohm-cm, which may be compared with the above mentioned 40 ohm-cm value generally accepted for the specific resistance of pure germanium. This measurement was only semiquantitative; however, it seems adequate to indicate that the previous resistance troubles had been due to contact problems in the experimental setup. These are considered next.

b. Sample Contacts

There are two clear and distinct problems grouped under this general heading. In practice a compromise must be effected, to minimize their joint effect. Thus, the electrodes must be highly conductive, relative to the photoconductive material. In the case of cadmium sulfide which is effectively an insulator in the dark, it was quite permissible to employ conducting glass electrodes with resistances in the range of 50 to 100 ohms per square . The dark current is negligible, so that illumination by a light spot clearly defines the coordinates for current flow. Since this current typically may be a few microamps, only a negligible potential drop would be incurred due to electrode resistance.

For pure germanium, however, the electrodes should be highly conductive since, even in the dark, germanium has a somewhat low resistance at normal room temperature. A typical single crystalline disc of diameter 1 cm and thickness 0.1 cm would have a calculated face to face resistance of 5.1 ohms. Unless the resistance of the contacting electrodes parallel to the crystal faces be considerably lower, say 0.5 ohms, it is not at all possible to establish a pattern of uniform current flow perpendicular to the crystal faces. If this is not achieved, then the potential between corresponding opposite faces of the crystal will not be uniform. This in turn, will result in an undesirable non-uniform photoresponse at various points.

The other aspect to be discussed here is the nature of the electrode-semiconductor contact. In general this would be expected to have a contact potential associated with it. Further complications are to be expected due to the presence, of surface impurities on both the sample and the electrode; often these are highly resistive oxide films. These effects together conspire to produce non-ohmic contacts which may effectively mask the enhancement. Observations of resistances as much as several thousand of ohms, rather than the expected 5.1 ohms for the experimental crystal discs used, suggested that contacts constituted a major problem, so considerable effort was spent on this aspect of the study.

The first step was to etch the crystals to expose clean faces. A standard etch, normally designated C.P. 4A, was employed. This is a mixture of nitric, hydrofluoric and acetic acids. The highest purity materials were employed. This treatment resulted in the appearance of smooth, shiny surfaces on the crystal. It was with such a specimen that the infrared spectral measurements mentioned above were made. Upon making contact to these surfaces with bulk metal, the apparent resistance was still a minimum of about 1000 ohms; it seemed that removal of the surface impurities was not sufficient to cure the contact problem.

Indium is commonly used to make ohmic contact to germanium, so the possibility of using a thin evaporated film was considered. At this point it was necessary to ensure that the lateral resistance of the film be low enough as described above. At the same time the film should be semi-transparent, for otherwise it would defeat its own purpose by not allowing light to penetrate to the germanium.

Tests were conducted by simultaneously monitoring the resistance and optical transmission of indium films during vacuum evaporation. It soon became apparent that the technique was not suitable, owing to the exceptionally high resistance of any films which were thin enough to pass much light. Support for this observation was found in the literature[(4)]. It would seem that indium nucleates upon condensing on a substrate, to form mutually insulated island crystals which only coalesce to a conducting layer at considerable thicknesses.

A much better material for contacting the specimens was found in electroformed copper mesh. This combines the requirement for lateral conductivity with a degree of transparency. The specimen which was employed was of 160 mesh/cm and 18 μ thick; it was obtained from Jelliff Corp., Southport, Connecticut. Its optical transmission, as measured in the near infrared on a Beckman DK 2 spectrophotometer, was less than 3 percent. By careful etching in a mixture of ammonium hydroxide and hydrogen peroxide, this transmission was increased to about 15 percent, equivalent to an optical density of 0.8.

Using this mesh to contact the germanium in the experimental cell by pressure, a persistently high resistance was still observed. For the special purpose of making resistance tests a relatively thick In layer was now deposited on each face of the cell. The cell was then reassembled with the copper mesh electrodes. This arrangement finally yielded reasonable resistance values as measured with an ohmmeter. Current-voltage plots were made for both polarities (Figure 4-6). This revealed a residual non-ohmic effect in two ways: there was a residual voltage at zero current, also the slopes (resistances) differed for the two polarities. However, by averaging the slope values the effect of this contact potential was eliminated, yielding a calculated resistivity value for germanium of 39 ohm-cm, which agrees with the usual figure for very pure Ge.

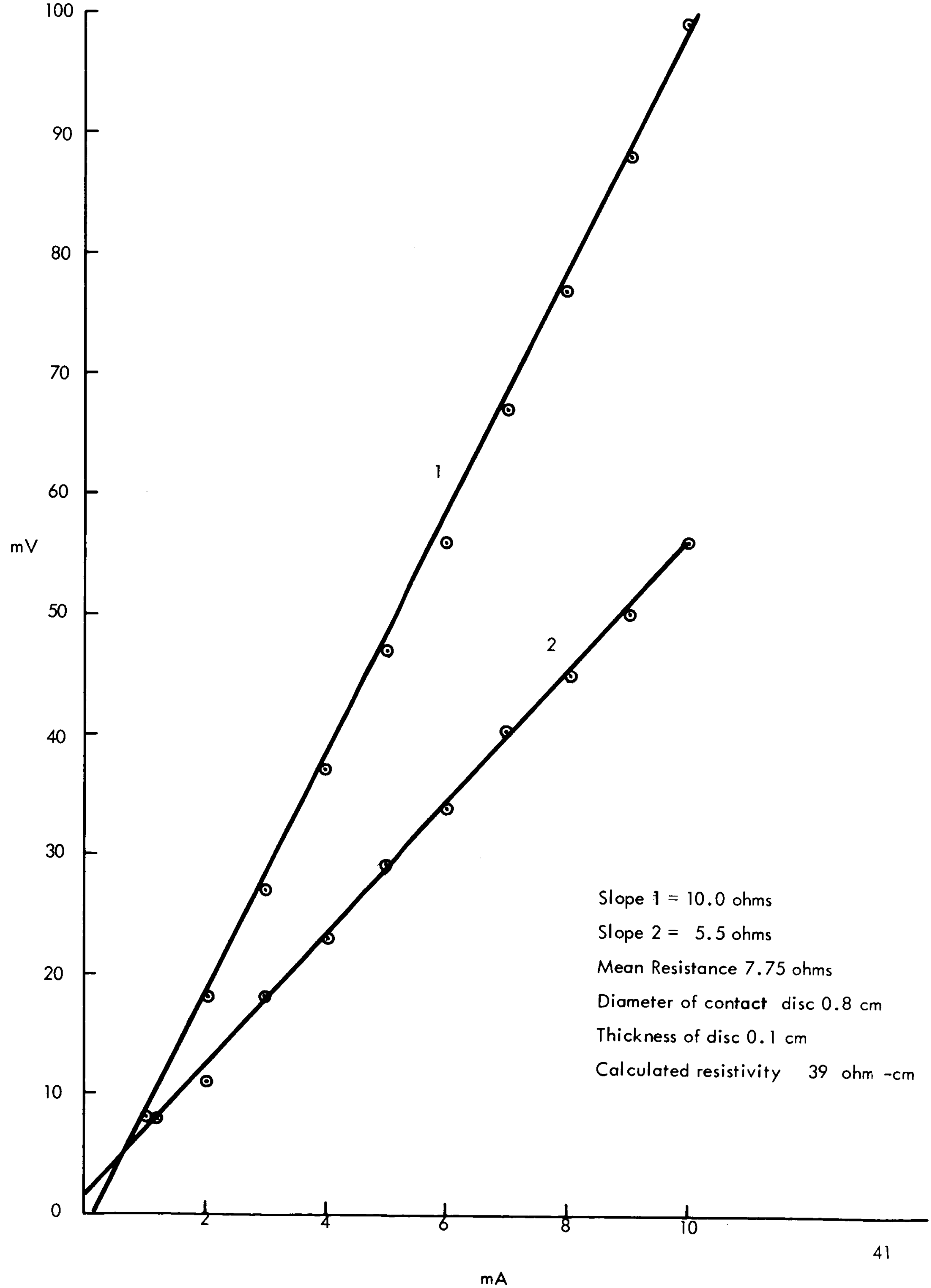
One possibility for future photoconductivity work would be to proceed with a copper mesh coated with In. This would provide good ohmic contact while allowing the light to pass unimpeded through the mesh holes.

An alternative would be to change from copper mesh to gold mesh, in order to avoid possible remaining perturbations from oxidation of the copper. Gold mesh 400 holes/in, 36 percent quoted transparency has been obtained from Ladd Industries, Burlington, Vermont.

The next section of this report turns from a description of the experimental work to a consideration of predictions from the theoretical model of the photoenhancement effect developed previously under this contract.

FIGURE 1-6

CURRENT-VOLTAGE PLOTS FOR Ge 2 SAMPLE



Slope 1 = 10.0 ohms

Slope 2 = 5.5 ohms

Mean Resistance 7.75 ohms

Diameter of contact disc 0.8 cm

Thickness of disc 0.1 cm

Calculated resistivity 39 ohm -cm

V. THEORETICAL MODEL

A one dimensional mathematical model of the enhancement effect was developed and presented in the previous summary report[5]. This was based upon a steady-state kinetic model for the charge carrier concentration. The differential equation describing this state is:

$$D \frac{d^2c}{dx^2} - \mu E \frac{dc}{dx} - kc + \alpha I e^{-\alpha x} = 0$$

where the first term represents the diffusion of the charge carriers, the second their motion in the field, the third their recombination (removal) and the fourth their generation by light absorption.

The constants are:

D, the diffusion constant of tne cnarge carriers

μ E, their drift mobility (mobility x electric field)

k, their recombination constant

α, the optical absorption coefficient at the wavelength used

The quantity I has dimensions of charge carriers cm^{-2} sec^{-1} and is proportional to the light intensity, while c is the equilibrium concentration of free charge carriers at a distance x from one surface.

The general solution leads to an unwieldy explicit expression for c in terms of the above properties.

A second, similar equation is applicable when illumination from the opposite side of the photoconductor is considered. In this case x is replaced by d-x, where d is the cell thickness. In addition, for the general case of asymmetric illumination, different characteristic parameters α', I', and c' must be used.

In order to obtain specific solutions to each of these equations, it is necessary to introduce boundary conditions for c and c'. When this is done, two new parameters c_o, and c_o', representing the equilibrium concentrations of the charge carriers at the surfaces appear.

The photocurrents are given by

$$i_1 = \frac{V}{R} = \frac{V}{\int_o^d dR} = \frac{V}{m\int_o^d \frac{dx}{c}}$$

Similarly $$i_2 = \frac{V}{m\int_o^d \frac{dx}{c'}} \quad \text{and} \quad i_T = \frac{V}{m\int_o^d \frac{dx}{c+c'}}$$

Where V is the applied voltage (constant)

R is the resistance of the irradiated material

and m is a proportionality constant.

Upon substitution into the expression for M (equation 3-1) we have

$$M = \frac{\left[\int_o^d \frac{dx}{c+c'}\right]^{-1}}{\left[\int_o^d \frac{dx}{c}\right]^{-1} + \left[\int_o^d \frac{dx}{c'}\right]^{-1}}$$

In this derivation, the contribution made by the minority carriers is assumed to be negligible.

We would like to test the theoretical model by inserting the correct values for the parameters into the expressions for the charge carrier concentrations and comparing the calculated value of the enhancement factor to the measured value.

After a rough enhancement factor of 4 was measured experimentally (see Chapter 4, Part D), the parameters applying to that experiment were used in a calculation to derive a theoretical value of M from the predictions of the model. For intrinsic germanium, the values of D, μ, and k are known[(6)] ($k=1/\tau$, where τ is the carrier lifetime). The absorption coefficient for intrinsic germanium is known as a function of wavelength[(7)]. We require the value of α ($=\alpha'$) at 1.3μ. The values of E and d were determined by direct measurements. I and I' are known in terms of irradiance, i.e., photons $cm^{-2}\ sec^{-1}$, and were converted to carriers $cm^{-2} sec^{-1}$ by assuming that the quantum efficiency is 1 carrier per photon.

The known values of the parameters are given below:

D	=	$100\ cm^2 sec^{-1}$	α	=	$7\times10^3 cm^{-1}$
μE	=	$5.7\times10^4 cm\ sec^{-1}$	α'	=	$7\times10^3 cm^{-1}$
k	=	$10^{-3} sec^{-1}$	I	=	10^{17} carriers $cm^{-2} sec^{-1}$
d	=	$0.1\ cm^{-1}$	I'	=	3×10^{16} carriers $cm^{-2} sec^{-1}$

Two parameters are unknown, c_o and c_o'; these are the surface carrier concentrations and there is no way of predicting their values <u>a priori</u>. However, a reasonable upper limit for each is a value equal to $I+I'$. Values of c_o and c_o' in the range from zero to 10^{18} carriers cm^{-3} were considered possible.

Calculation of the M value was carried out on the UNIVAC 1108 system using the ALLSTEP program [8]. The computation of M was made for an array of c_o and c_o' values; the values of each ranged from 10^6 through 10^{18}. For each (c_o, c_o') pair, M was computed with the other eight parameters having the values listed above. In every case the predicted value of M was not significantly different from 1 although over one thousand computations were made. However, M was also computed for a range of values in each of the eight "known" parameters. In this manner we allowed for the uncertainties in the values of the material parameters and in the experimental conditions. It was found that variation of the value of μE yielded M values greater than 1. In the theoretical model this parameter is assumed to be a constant throughout the photoconductor. This assumption is, of course, not quite accurate [9] and so we should expect the effective value of μE to be known less accurately than the values of the other "known" parameters.

We give below, some selected values of c_o, and c_o' and μE which yielded M values significantly greater than 1. The other parameters have the values listed above.

	c_o	c_o'	μE	M
1.	10^8	10^8	5.7×10^3	2.1
2.	10^8	10^{12}	5.7×10^3	4.8
3.	10^8	10^{16}	1.4×10^4	3.7
4.	10^{12}	10^{16}	1.4×10^4	2.6

These results indicate that, within the limits of our assumptions about c_o, c_o', and μE, the model could be construed to predict a small enhancement effect under the conditions of our experiment. However, the experimental resistance troubles already described indicate that the comparison of these results with the experimental values regarded as still uncertain should be postponed, until the experimental parameters have been brought under better control.

VI. CONCLUSIONS AND RECOMMENDATIONS

When a layer of photoconductive material is illuminated by a small spot of light on one face and another spot on the reverse side such that the two spots are arranged to be just opposite each other, an enhancement in the photoconductivity of the material occurs - beyond the amount of photoconductivity present when the same two light spots are not coincident.

As observed in layers of polycrystalline cadmium sulphide deposited on conducting glass, facts about the enhancement phenomenon are now established, thus:

1. The greatest enhancement observed to date, a factor of about 1000, occurred with the two beams having wave lengths of 533 mμ and 512 mμ with spot diameters no greater than 0.05 cm and with a CdS layer thickness in the range of 50 to 75 μ with an applied field of 1V. The wavelengths used are in the absorption edge region for CdS.

2. The effect was found to be optimum for a remarkably low value of power incident on each surface - about 0.7μ W - cm^{-2} in the wavelength range of 500 to 550 mμ.

3. It was found that the effect decreased with increasing electric field, falling asymptotically to a value only a little greater than unity.

4. The value of the enhancement factor, M, was found to be directly proportional to the degree of spot overlap.

5. For the layer thicknesses used, the value of M was found to peak for light spot diameters of about 0.1 cm. No enhancement occurred for full illumination of the crystal faces.

In addition to the CdS experiments, work has commenced on the development of methods for the measurement of photoconductivity in infrared sensitive materials. Initial experiments with single crystalline germanium gave at least slight indications that enhancement could occur. This was supported by calculations based upon the mathematical model of the effect.

It is proposed to conduct parallel experiments on monocrystalline specimens of silicon.

The study of possible applications under this contract (which will be reported in some detail at a later date) indicates that many applications will require faster response than has been observed so far for CdS at low light levels. For this reason the emphasis of the next period will be placed not only on CdS, but also on Ge and Si which might be expected to have a much faster response at low light levels.

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A PHYSICAL MODEL FOR

TEKTITES OF METEORITIC ORIGIN

I. ANALYSIS OF DATA AND PHENOMENOLOGICAL BASIS

J. L. Remo*

Institute for Space Studies
Goddard Space Flight Center, NASA
New York, New York

and

Department of Physics and the
Department of Earth and Space Sciences
State University of New York at Stony Brook

and

A. J. Skalafuris

Institute for Space Studies
Goddard Space Flight Center, NASA
New York, New York
10025

and

Department of Physics
City College, New York
10031

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