GERMANIUM IN ELECTRICAL CIRCUITS AND ITS ELECTRICAL PROPERTIES

by

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INTRODUCTION

The work done in connection with this thesis represents some of the more important measurements of characteristics of impurity semiconductors, and the application of semiconductors in electrical circuits. The semiconductor used for this work was usually germanium.

Measurement of Characteristics of Semiconductors

Intensive work in the field of semiconductors has been carried out since 1930, and even more concentrated effort was made after the Second World War to gain physical information about semiconductors and the mechanism of conduction processes in these materials. Many types of measurements were made to determine structure, conductivity, types of charge carriers, concentration of carriers, mobility of carriers, temperature effects, effect of impurity concentrations, and numerous allied physical characteristics.

One of the more important measurements is based on the Hall effect from which, when the conductivity of the material is known, it is possible to determine the concentration, mobility, and type of carriers. The Hall effect, discovered in 1879 by E. H. Hall, is evidenced by the change of path of carriers in a magnetic field from the direction of the applied electric field which causes a potential difference and hence an electric field to be produced in the transverse direction. The applied magnetic and electric fields are normally at right angles to each other.

For at least two reasons it is desirable also to determine mobilities by a method other than the Hall effect. The Hall effect determines effectively the carrier mobility between collisions, which will be slightly greater than the macroscopic or drift mobility. Thus to verify the theory of collision processes and the average effect on mobility over an appreciable length of impurity semiconductor it becomes necessary to measure the drift mobility. Also from considerations of an applied nature resulting from problems of delay time and frequency response in impurity semiconductors used in electrical circuits, the value of the drift mobility is a desired quantity since electrical connections to semiconductors are of necessity macroscopic. For the purpose of measuring the macroscopic mobility it would seem that from the Hall effect measurement and a theoretical value of the ratio of the Hall mobility to the drift mobility due to collision effects one could calculate the drift mobility. A good approximation does result from this method, however, the theoretical value, $3\pi/8$, of the ratio of the Hall mobility to the drift mobility is seldom found in practice. A more complete description and results of Hall and drift mobility measurements can be found in Shockley, pp. 209-217, 336-341, Shockley (10).

Semiconductors in Electrical Circuits

The first large scale use of semiconductor materials in electrical circuits was initiated during World War II. Point contact units made mainly of silicon crystals provided small, efficient rectifiers and mixers for use at microwave frequencies.

The possibility of the use of semiconductors for A. C. power amplification seems to be first indicated by Torry and Whitmer (12). These authors described crystal rectifiers with negative input resistance characteristics. The work done during World War II in the development of crystal rectifiers as described by the above authors solved many of the technical problems in the production of semiconductor devices.

The first practical crystal amplifier device was developed by Bardeen and Brattain (1) in 1948. Their device consisted of a block of germanium of millimeter dimensions with a large, low resistance contact on one surface, and two closely spaced point contacts of high resistance on the opposite surface. The crystal amplifier was named the transistor because of its transfer of resistance characteristics. Usable frequencies for the unit were below 10 MC and power dissipation was considerably less than one watt. Although frequency characteristics and power ratings have been changed somewhat the general properties and construction of the point contact or type A transistor have been modified very little.

Following the development of the point contact transistor the junction transistor was developed. This device, as now used (1956), consists of semiconductor crystals which contain varying and controlled amounts of impurities. The advantages of the junction transistor over the point contact are:
(1) lower supply voltages, (2) higher power ratings, (3) higher collector impedance resulting in greater power amplifications at lower currents,
(4) better control in manufacturing. The main disadvantage of both the junction and point contact transistors is the frequency limitation but this is not considered intrinsic.

Recent units (1955) indicate power ratings above 60 watts collector dissipation and usable frequencies above 500 megacycles per second although not for the same units.

Transistors are probably best thought of as circuit components. While it is true that they amplify and are used in locations identical with those in which vacuum tubes are used, they are also used for purposes which would not normally require vacuum tubes. As an example, transistors are finding use in interrupting d.c. in power supplies as an improvement over vibrators.

In order to use transistors commercially or to compare various types of transistors it is necessary to know both their static or d.c. and a.c. electrical characteristics. Since the a.c. characteristics are functions of the operating currents and voltages, the operating point must be specified. When the operating point is known, the a.c. characteristics may be measured directly or, as an alternative, a set of graphs plotted for a number of operating conditions may be used to determine how the transistor will function in a circuit.

There are four variables which are determined by the quiescent condition of a transistor. They are the collector voltage and current, and the emitter voltage and current. Excluding such things as temperature effects the specification of any two of the variables determines the other two. However, the currents may be double-valued functions of the voltages while voltages are single-valued functions of the currents. For this reason the currents are usually taken as the independent variables.

Using the common base connection and conventional direction for currents in a four-terminal active network the emitter current and voltage are normally positive and the collector current and voltage negative.

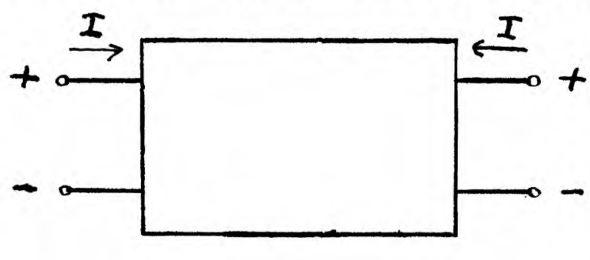


Fig. 1. Conventional polarity for a four-terminal active network.

In order to examine the a.c. characteristics for small signals, from the static or d.c. characteristics we may write:

$$(1) \qquad \Delta V_e = r_{11} \Delta I_e + r_{12} \Delta I_c$$

$$(2) \qquad \Delta V_c = r_{21} \Delta I_e + r_{22} \Delta I_c$$

Where the open-circuit resistance parameters are defined as:

$$r_{11} = (\partial V_e / \partial I_e)\ I_c$$

$$r_{12} = (\partial V_e / \partial I_c)\ I_e$$

$$r_{21} = (\partial V_c / \partial I_e)\ I_c$$

$$r_{22} = (\partial V_c / \partial I_c)\ I_e$$

the subscripts indicating constant values.

The current amplification factor, α, is defined by

$$\alpha = \left| \partial I_c / \partial I_e \right|_{V_c}.$$

Thus equation (2) may be written in the form

$$\Delta V_c = r_{22}\ (\alpha \Delta I_e + \Delta I_c).$$

The parameters are measured by using the ratio of small a.c. voltages and currents since, as an example:

$$r_{11} = (\partial V_e / \partial I_e)_{I_c} \simeq (\Delta V_e / \Delta I_e)_{I_c} \simeq (v_e / i_e)_{I_c}$$

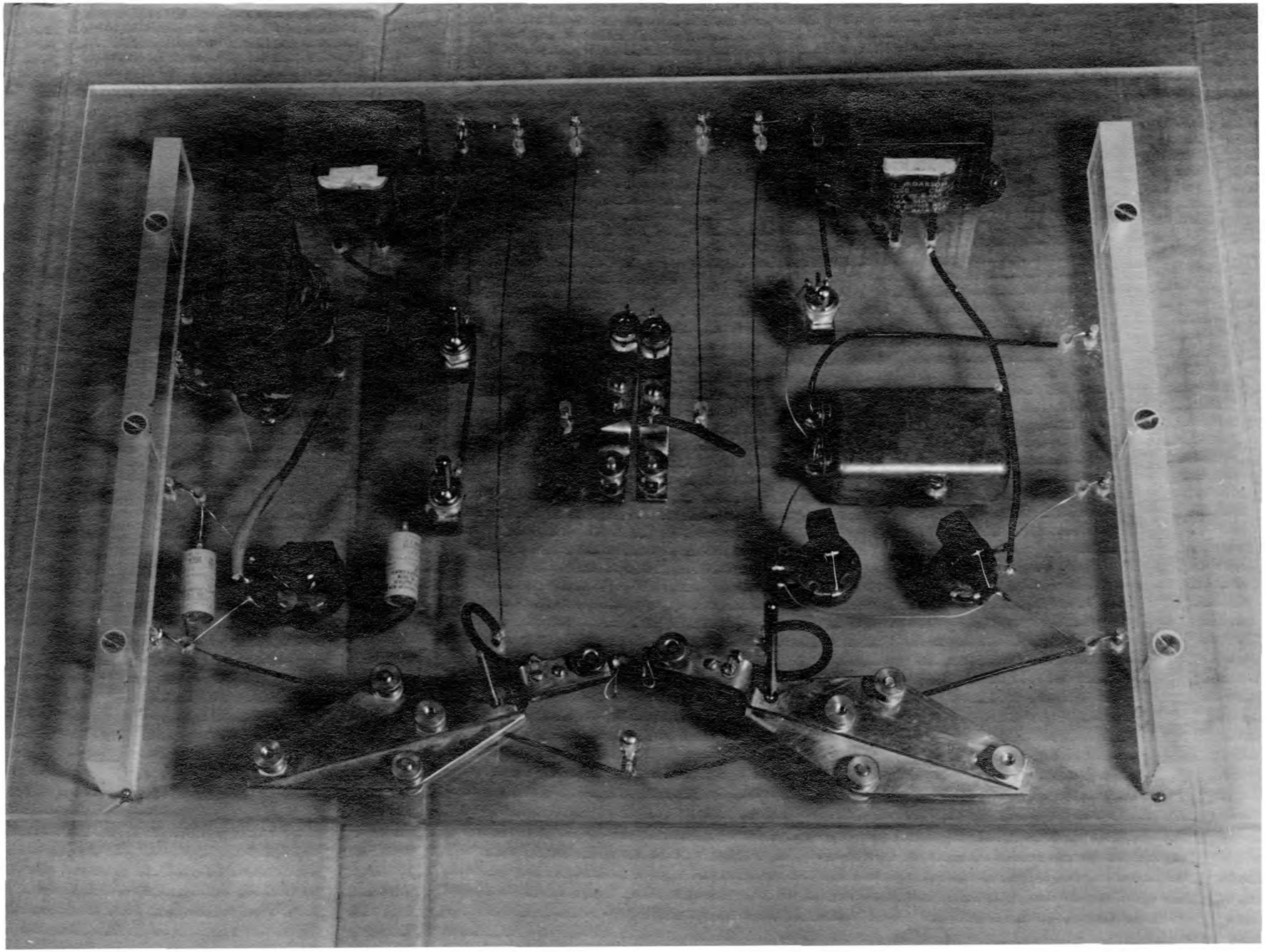
The actual measurement of the parameters consists of connecting a generator to the emitter circuit, adjusting the d.c. operating point, and then with the collector circuit open to a.c. measuring v_e and i_e to find r_{11}. Without changing the circuit v_c is measured to find r_{21}. The generator is then moved to the collector circuit, the emitter circuit opened to a.c. and v_e and i_c measured to find r_{12}. Finally v_c is measured to find r_{22}.

The test circuit as shown on Plate I allows these measurements to be made with the proper selection of switch positions.

EXPLANATION OF PLATE I

Photograph of testing circuit used to test for transistor action and to compare various transistors and transistor circuits. With this circuit it is possible to measure the a.c. characteristics of transistors at differing operating points and to try transistors in any of the three circuit configurations operating into various loads. A schematic is shown on Plate II.

PLATE I



A discussion of other types of parameters and those used in grounded emitter and grounded collector applications may be found in Shea (8).

Statement of Purpose

The purpose of the work done in connection with this thesis was to measure some of the important electrical characteristics of semiconductor materials and to construct transistors from such materials and examine the application of these transistors to electrical circuits. To this end the work quite closely followed a set of experiments devised by The Bell Telephone Laboratories. Of considerable guidance in making measurements was the book, Electrons and Holes in Semiconductors, Shockley (10).

POINT CONTACT TRANSISTORS

Several point contact transistors were constructed with various surface treatments and mechanical constructions. These transistors were made from crystals of silicon, germanium, galena, and pyrite. Only those transistors using germanium crystals grown specifically for use in transistors showed a greater output voltage (collector to base) than input voltage (emitter to base) when used in the circuit shown schematically on Plate II. Crystals from semi-conductor diodes and natural crystals indicated good rectification characteristics but no voltage amplification.

In constructing the transistors the crystals were lapped with 600 mesh alundum, then etched in CP-4 solution which consisted of:

25 ml conc. nitric acid

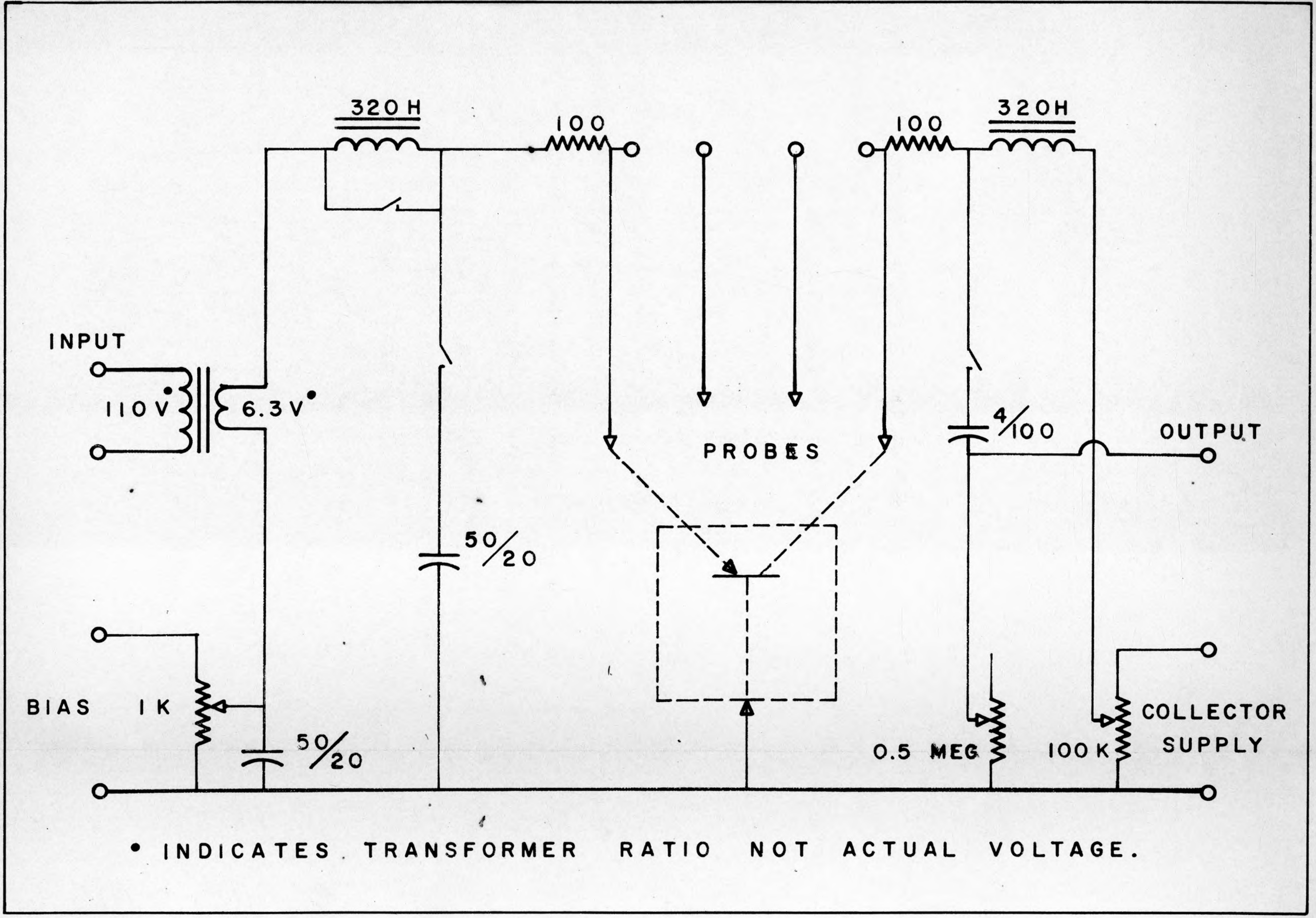
15 ml glacial acetic acid

15 ml hydrofluoric acid

a few drops bromine

EXPLANATION OF PLATE II

Schematic diagram of testing circuit shown on Plate I. A pnp transistor is shown in the diagram in the grounded base arrangement. Capacitors are marked in μfd/volt.


320 H
100
100
320H
INPUT
110V•
6.3V•
PROBES
4/100
OUTPUT
50/20
BIAS
1K
50/20
0.5 MEG
100K
COLLECTOR
SUPPLY
• INDICATES TRANSFORMER RATIO NOT ACTUAL VOLTAGE.

The crystals were usually waxed to a piece of platinum wire for etching and were sometimes sandblasted before etching. Occasionally a drop of the CP-4 solution was placed directly on the surface to be etched. Only one surface, the working surface, was etched. Finally the crystal was washed in distilled water, dried with filter paper, and the etched surface protected with ceresin wax.

When the crystals were not previously plated and mounted, the side opposite the working surface was plated with rhodium. Usually the plating was done on a sandblasted surface although similar results were obtained by plating on an etched surface. The plating bath consisted of:

49 ml distilled water

1 ml Baker's rhodium plating solution #219

few drops of sulfuric acid to clear the solution.

The bath temperature was maintained between 45° C and 50° C by the use of a heat lamp placed approximately two feet from the bath. The positive electrode was a platinum wire. Plating time was considerably longer than that specified in the original Bell Laboratory experiments. Plating time was at least thirty minutes and the plating process was continued until the surface electrical resistance was quite low (10 ohms). A substantial change in surface color resulted from the plating.

If plating times longer than 30 minutes were used it was necessary that the bath solution be changed several times. Several modifications of the plating technique were tried. One modification was to reverse the electrode terminals occasionally during the plating. This and other methods tried produced no apparent improvement over the method described above.

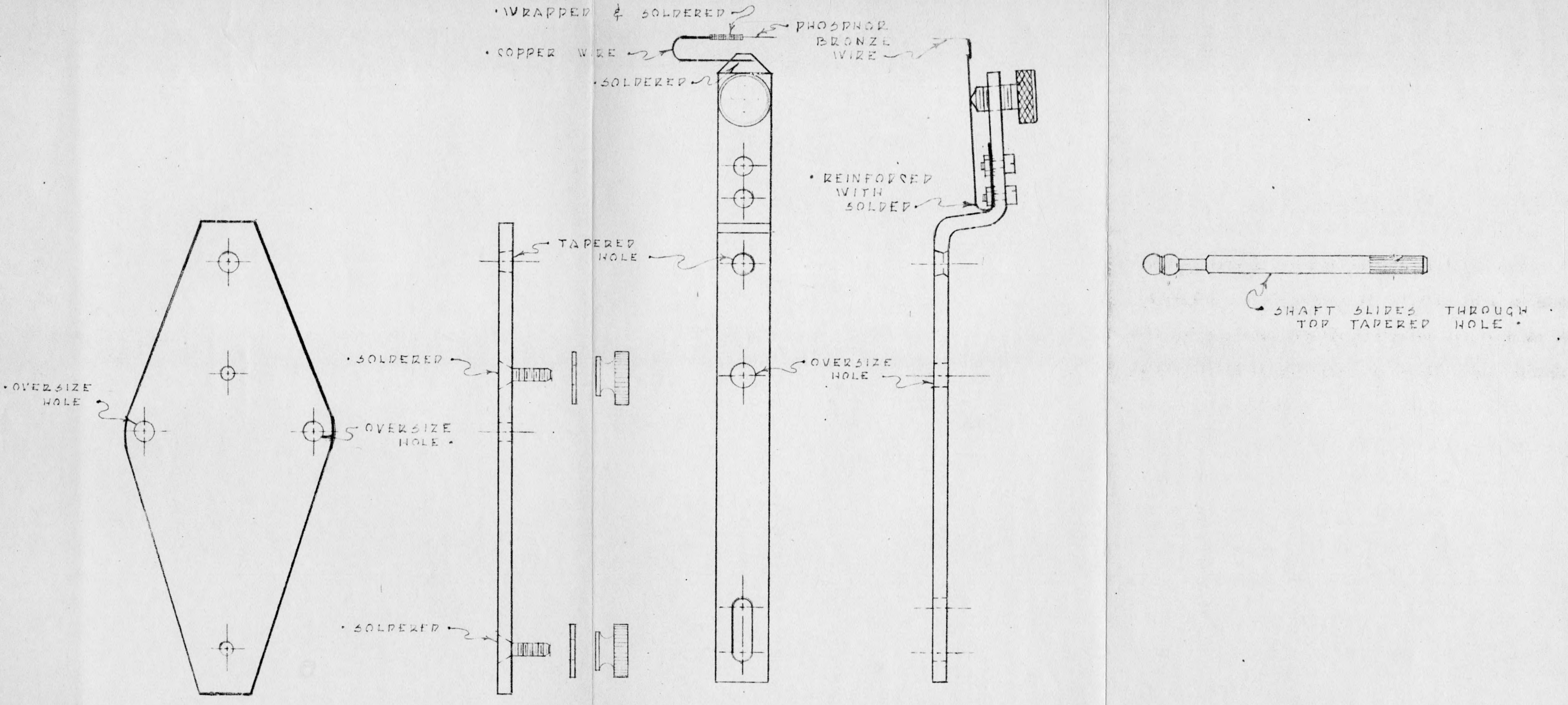
Electrical connections to the base or plated area were not critical and transistors were constructed using both soldered and mechanical connections. Successful base connections were also made by soldering to an unplated surface. Solder used was rosin core solder or rosin flux and pure tin.

Connections for the emitter and collector were phosphor bronze catwhiskers. Both cone and chisel points were used. The cone point was preferred because of the ease in shaping the point. The cone points were made by rotating the end of the wire against a rouged buffing wheel. Points made in this way were smooth, sharp, and symmetrical. These characteristics were valuable when distances between contacts were measured. The size of the wire used for the catwhiskers seemed to be of little importance. Wire with diameters of 0.016 inch were quite rigid and more easily controlled than the finer wire of 0.005 inch diameter. Control of the position of the emitter and collector points was quite difficult. Requirements for the placement of the points were approximately 1 cm of two-directional, transverse movements and 4 mm vertical movement. The required accuracy of placement in transverse movements was approximately 0.1 mm. In addition to these requirements it was necessary that the position of the point could be locked to prevent accidental movement. The catwhisker point manipulators described in the Bell Laboratory experiments did not meet these specifications. A construction diagram of the manipulators used is shown on Plate III.

After the three electrical connections were made to the crystal it was necessary to form the collector electrically. See Plate IV for the circuit used. Forming consisted of discharging a capacitor of .25 mfd at 300 V. between the base and the collector. The positive terminal of the capacitor was connected to the base for n-type germanium. This is in contradiction with the original forming instructions as given by the Bell Laboratory experiments

EXPLANATION OF PLATE III

Construction diagram of point contact manipulators used to give accurate and fixed, three directional control of emitter and collector points. Shaft shown is of mild steel. All other parts except those marked are of brass.



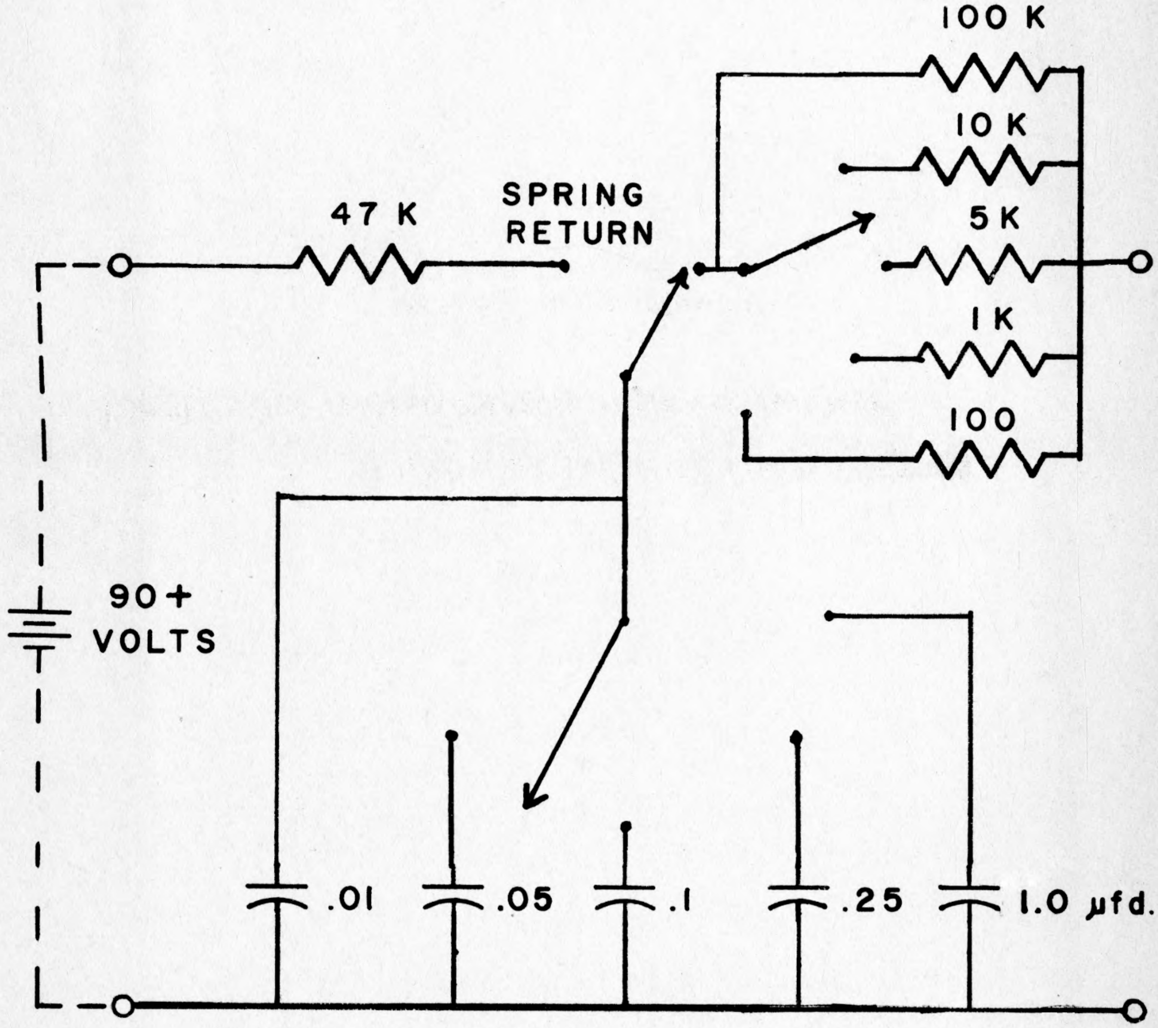
·POINT CONTACT MANIPULATOR·

SCALE = FULL SIZE

EXPLANATION OF PLATE IV

Schematic of simple forming circuit which provides flexible control of amount of forming.

PLATE IV



FORMING CIRCUIT

but agrees with the discussion of forming as given by Shockley (10). It is also in disagreement with the forming used in later experiments. No explanation of these anomalies in forming was attempted.

After the transistors were constructed they were put in the circuit shown on Plate II to test for transistor action. Since the transistors built drew power from the input generator the term amplification would apply better to power amplification. However, amplification as used in these trials applied to voltage gain as determined by dividing the peak to peak a.c. voltage from collector to base by the peak to peak a.c. voltage from emitter to base. Only the absolute gain and not the polarity was considered. Transistor action then as used here means a voltage gain which resulted from the use of a transistor in the test circuit shown in Plate II.

The transistor configuration used for these tests was the grounded base circuit. A photograph of the actual testing circuit used is shown in Plate I. Input to the emitter was a sine wave of the order of one tenth of a volt peak to peak.

Results obtained with this circuit and various experimental transistors showed voltage gains up to one hundred and twenty five without noticeable distortion. Gains of two hundred and eighty were obtained with extreme distortion. Gains of this magnitude were believed to be the result of excessive feed back within the transistor. Various operating points were tried with representative direct current values of two milliamperes emitter current and four and one-half milliamperes collector current.

At some operating points the transistor was unstable and produced oscillations having a frequency of approximately six megacycles.

Variations in gain produced by emitter-collector separation or other changes in construction were not measured since such variables have been investigated by others, and was not one of the objectives of this work (Bardeen and Brattain, 2).

A description of commercial production of type A transistors may be found in Coblenz and Owens (3) or Fahnestock (5).

DRIFT MOBILITY

Preparation of Crystals for Mobility Measurements

Germanium rods of high resistivity and long carrier lifetime characteristics were obtained from the Bell Telephone Laboratories. The rods as obtained had been cut to approximate size with a diamond saw but were otherwise unfinished. The rods were about two centimeters long with a square cross section of approximately one millimeter on a side.

The rods were ground smooth using 600 grit alundum and distilled water. Lapping to any particular dimensions was not attempted since only uniformity of cross section was desired. Crystals were held with the fingers for lapping.[1]

After lapping the rods were coated, except for about 4 mm on each end, with a heavy layer of polystyrene cement. The uncoated surfaces were then lightly sandblasted with 220 grit alundum. The abrasive was placed in a wash bottle, similar to the type used in chemistry, and a compressed air line provided the air supply. Some difficulty was experienced as a result of moisture in the compressed air which caused the abrasive to stick to the wash bottle and thus control of the amount of abrasive striking the crystal was lost.

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[1]The extra precaution of wearing rubber gloves, as is often done in commercial transistor work, was not tried.

Occasionally the crystal rods would become rounded on the edges and pitted from non-uniform sandblasting.

After sandblasting additional parts of the working surfaces were coated with polystyrene cement leaving only 2 mm of the ends exposed. Extreme care was used at this point of crystal preparation to prevent difficulties in the plating procedure which followed. Exposed surfaces were never touched with the hands or tweezers. When the surfaces were examined closely precautions were taken to prevent the breath from reaching the crystal.

The exposed ends were then plated with rhodium using the 10 per cent Baker plating solution as described in the section on point contact transistors. Plating current used was between 3 and 10 ma. The directions for plating in the Bell Telephone Laboratory instructions called for 3 ma but plating time was often shortened by using higher current values. The plating was continued until a transverse resistance measurement of the plated surface indicated less than 10 ohms. It was necessary to make a metallic connection to one end of the rod while plating the other end. This connection was made by use of an latered alligator clip which often caused a discoloration of the exposed surface and the plating on the second end was usually not as even textured as on the first. Difficulty in plating might have been lessened by using a platinum electrical connection to the crystal. With ordinary precaution the plating seemed to be satisfactory and for this reason the problem of obtaining smooth plated surfaces was not pursued further.

Plating time depended to a large extent upon the temperature of the plating bath. The temperature of the bath was maintained near 50° C by a heat lamp placed a few feet from the bath. No damage to the crystal was noticed from the increase of crystal temperature caused by the accumulative effect of high plating current and the applied heat. Recommended maximum crystal temperature as indicated by the Bell Laboratory experiments was 200° C.

The polystyrene cement was removed from the crystal by several rinsings in toulene. After the crystal was clean the sandblasted and plated areas were coated with cement and fastened to a wire. The wire used was a copper wire coated with polystyrene but a platinum wire would have been more satisfactory. The crystal was then submerged in the CP-4 solution described in the section on point contact transistors for several minutes, producing an etched surface which appeared quite smooth and had a metallic sheen when properly prepared.

The rod was then washed in distilled water and the polystyrene cement again removed with toulene. Following this the crystal was placed in an antimony oxychloride (SbOCl) suspension prepared by dissolving antimony chloride ($SbCl_3$) crystals in distilled water. One of the plated ends of the rod was connected to the positive terminal of a 1.5 volt cell and the negative terminal of the cell was connected to a platinum electrode placed in the suspension. After approximately five minutes the rod was removed from the suspension, thoroughly rinsed in distilled water and dried. This treatment of the etched surface with antimony oxychloride was intended to increase the lifetime of minority carriers since the majority of recombination is believed to occur at the surface.

Finally the crystal was coated with ceresin wax by submerging it in the molten wax for a few minutes and then wiping off the excess wax. The rod was then ready for the Hall and drift mobility measurements.

Measurement of Drift Mobility

When holes or electrons are injected into a semiconductor crystal which has an internal electrical field they will drift with a velocity determined by the field and the crystal.

The drift mobility is defined by

(1) $$\mu_D = v/E$$

where v is the average velocity of the charge carrier and E is the electric field. Since $v = L/t$ and $E = V/L$ we may write equation (1) in the form

$$\mu_D = L^2/Vt$$

where V is the potential difference, and t is the time it takes minority carriers to move a distance L.

The measurement of the mobility consists then, of measuring the voltage between two probes, the distance of separation of the probes, and the time it takes the injected holes or electrons to reach the second probe.

Hall effect measurements as described in the next section measure mobilities from side effects produced in a magnetic field and in special cases the ratio of the Hall mobility to the true or drift mobility will be the usually accepted value of $3\pi/8$.

Procedure

A photograph of the experimental arrangement used for this measurement is shown in Plate V. Slight modification of the testing circuit was required for this measurement. The emitter and the collector probes were placed on the crystal and the collector formed by discharging a 1.0 μfd capacitor charged to 125 volts through the collector with the collector positive. Opposite polarity in forming produced no apparent effect on the collector. The polarity used was the reverse of the forming used for the point contact transistors and no explanation for this discrepancy was found. Positive pulses of 0.5 microseconds duration at a repetition rate of 60 pulses per second were injected at

EXPLANATION OF PLATE V

Fig. 1. Photograph of experimental arrangement used to determine drift mobilities. Interconnecting wires are not shown to avoid confusion.

Fig. 2. Photograph of crystal rod and point contacts used in drift mobility measurements.

PLATE V

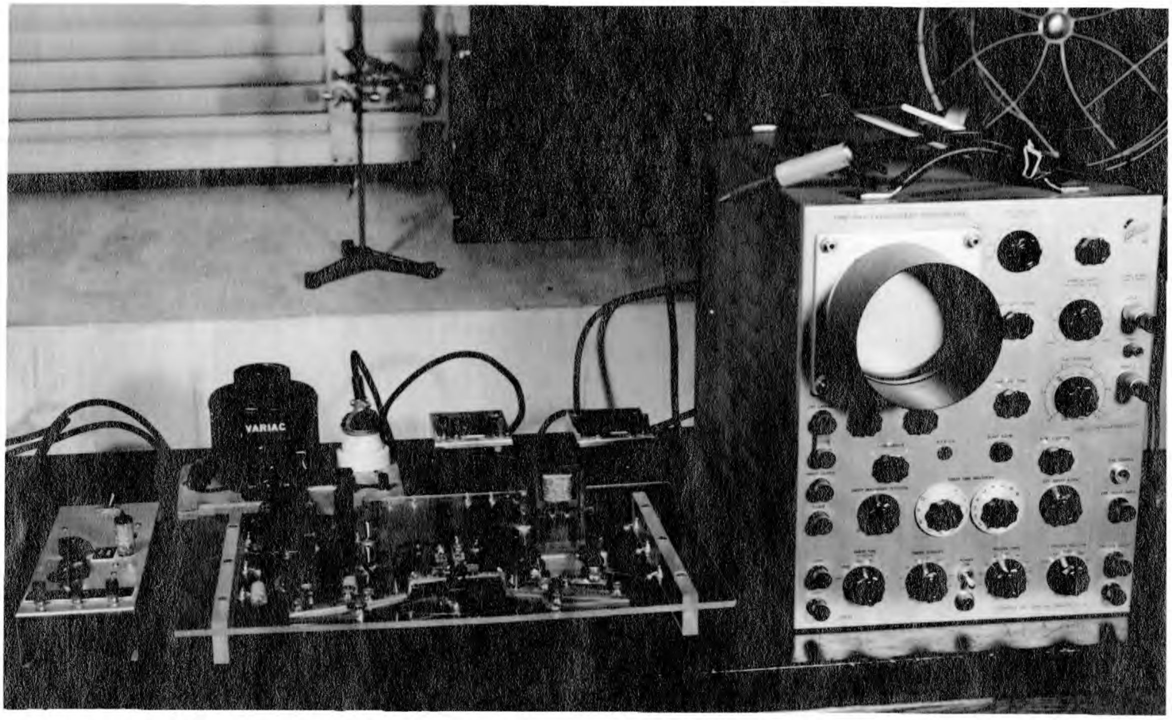


Fig. 1

Fig. 2

the emitter. The time of arrival of each pulse at the collector as well as the time of the initial pulse was determined by the resulting oscilloscope pattern on a syncronized oscilloscope having a delayed pattern.

The distance of separation between the emitter and collector was measured with a travelling microscope. The potential difference between the probes was measured as before with a vacuum-tube voltmeter. Drift time was determined by measuring the distance between the initial pulse and the second pulse on the oscilloscope and dividing by the sweep velocity.

Initial variations in the results obtained for the drift mobilities were attributed to a non-linear voltage gradient in the crystal. Therefore, the crystal was replated, and the voltage gradient was examined for linearity. A current of approximately 10 ma was allowed to flow in the rod and the potential vs displacement, as measured with a vacuum-tube voltmeter, at a number of points along the crystal, was plotted as shown in Plate VI. The slope of the resulting curve indicated a nearly constant potential gradient.

Since the current through the crystal raised its temperature above room temperature and since the mobility varies as $T^{3/2}$ it was necessary to make a temperature correction. It was assumed that the change in temperature was proportional to the square of the current[1], that is

$$\Delta T = k (I)^2$$

and that the actual temperature of the crystal was then

$$T = T_o + k (I)^2$$

where T_o was the absolute ambient temperature. The constant k was evaluated

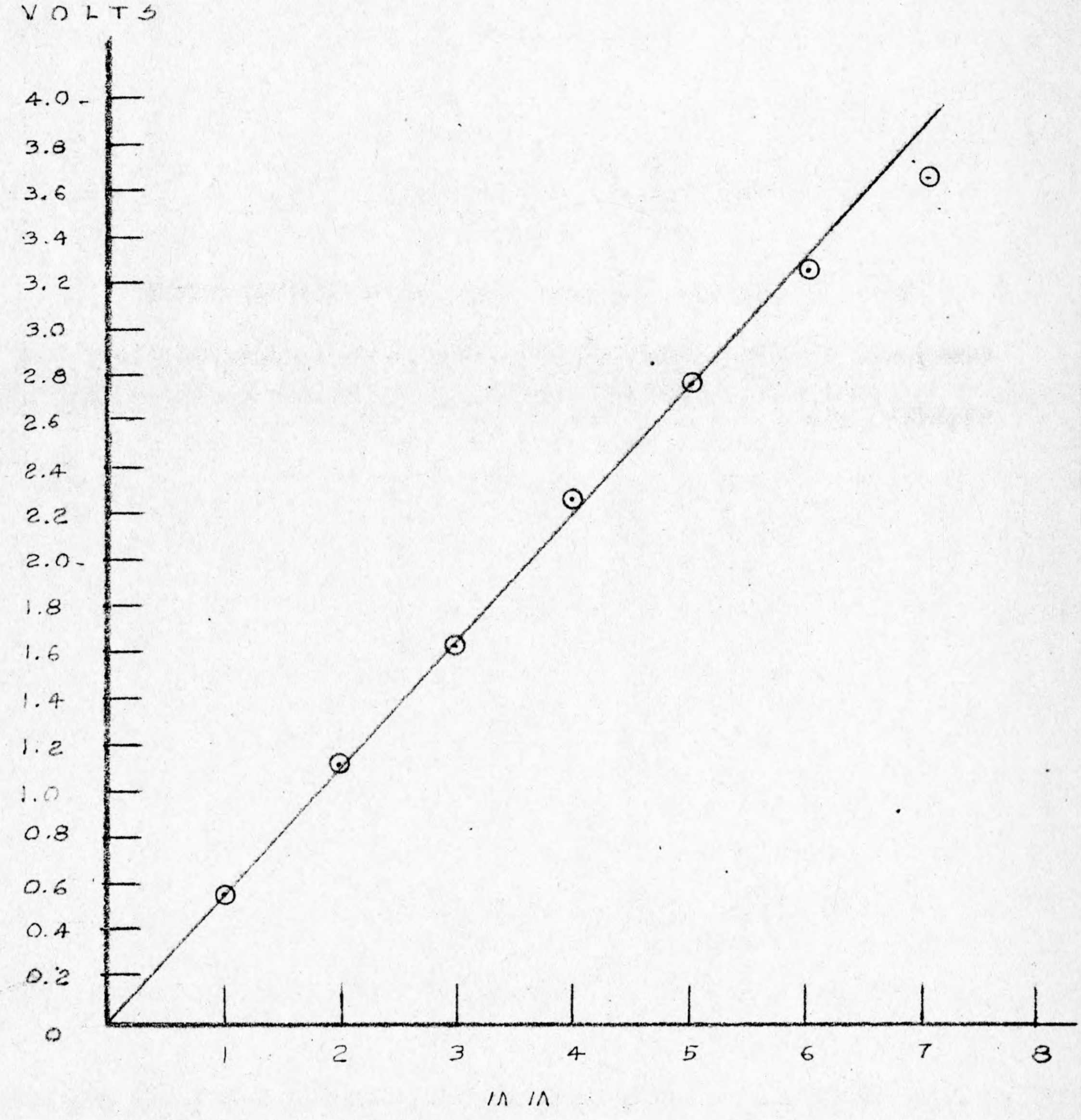
[1]Since in the equilibrium condition the electrical power input was equal to the rate of loss of energy in the form of heat, the assumption was that the rate of loss of heat energy was proportional to the absolute temperature. Although this assumption may not have been completely valid, the correction was in the right direction.

EXPLANATION OF PLATE VI

Graph of voltage vs probe separation showing nearly constant potential gradient and indicating a homogeneous crystal rod.

PLATE VI

VOLTAGE vs EMITTER
COLLECTOR SEPARATION
CURRENT IN ROD: 10 MA.
COLLECTOR FIXED AND FORMED



by noting the current through the crystal which just melted a thin layer of ceresin wax of a known melting point.

Data

Trials 1 and 2 were not recorded since faulty plating of the crystal produced inconsistent results.

Table 1. Measurements obtained in determining the drift mobility.

Trial	Probe separation (mm)	Drift Time (μ second)	Voltage between probes (volts)	μ_D (cm^2/volt-sec.)	Deviation
3	5.00	48.2	2.89	1770	-20
4	4.00	38.0	2.38	1770	-20
5	3.00	28.0	1.80	1790	0
6	3.00	27.5	1.82	1800	+10
7	2.00	17.9	1.23	1820	+30

Average $\mu_D = 1790 \pm 13$ cm^2/volt-second

$$k = .12\ ^{o}C/ma^2$$

$$T = 299 + 12 = 313\ ^{o}K$$

$$(\mu_D)_{300^o K} = 1790\ (300/313)^{3/2} = 1790 \times .939 =$$

$$1680 \pm 16 \text{ cm}^2/\text{volt-sec.}$$

Accepted value of $\mu_{D_{300}} = 1700$ cm^2/volt-sec.

The greatest error in measurement was attributed to the measurement of the distance on the oscilloscope pattern between the initial pulse and the peak of the second pulse.

The error of this measurement was probably no greater than 4%. Since the other measurements involved seemed to be accurate within less than 1% error, the total error of measurement for the drift mobility was believed to be less than 6%. Thus the result for the drift mobility at ambient temperature was 1700 $\pm$ 100 cm^2/volt-sec. This agrees quite well with previously reported results of 1700 $\pm$ 90 cm^2/volt-sec., Shockley (10), p. 337.

Conclusions from Mobility Measurements

Accurate and consistent results were obtained with this method when crystals were properly prepared. However, the necessary equipment and time involved in making measurements indicated a need for a more straight forward method to measure or compare mobilities. It is quite important to note that the measured mobility was a monotonic decreasing function of probe separation. No explanation of this variation was found.

HALL MOBILITY

Important in the development and confirmation of the theory of conduction processes in semiconductors is the measurement of the mobility of carriers in semiconductor crystals by a method other than that previously described. One of the methods of measuring mobility involves the Hall effect. The Hall effect results from carrier movement in crossed electric and magnetic fields in which electrons or holes move in cycloidal paths until they suffer a collision after which they begin an essentially new path. The cycloidal paths and collisions produce a transverse motion of charge which in the equilibrium condition produces a potential difference and hence an electric field across the crystal in a direction perpendicular to the original electric and magnetic fields. The magnitude of the potential difference depends upon the magnetic field, the applied electric field, crystal dimensions, and the mobility of the carriers. Thus, since the other quantities can be readily measured, the mobility of the carriers can be determined.

One fundamental difference between Hall effect measurements and drift measurements as described in the previous section is that the Hall measurement involves the majority carriers as opposed to the drift method of measurement based upon the injection of minority charges. Of practical interest the Hall measurement involves much less equipment, is much more readily obtained and computed with the proper equipment, and for commercial purposes gives a better estimate of the suitability of a semiconductor for circuit devices.

The theory of the Hall effect may be developed by considering the force on a carrier in the direction of the transverse electric field produced by the Hall effect. (Let this be taken as the Y direction, the applied electric field in the X direction, and the applied magnetic field in the Z direction). Then since the applied fields are perpendicular, the force in the Y direction in c. g. s. units due to the magnetic field will be

(1) $$F_h = -(q/c)v_x H_z$$

while the force in the Y direction due to the transverse field is

(2) $$F_E = qE_y \text{ .}$$

Since in the equilibrium condition

(3) $$F_h + F_E = 0$$

(4) $$(q/c)\ v_x H_z = qE_y \qquad \text{or} \qquad E_y = V_x H_z/c$$

The Hall mobility, μ_h, is defined as

(5) $$\mu_h = v_x/E_x$$

where v_x is the velocity as used above and is therefore the velocity between collisions in the longitudinal direction.

(6) $$E_y/E_x = v_x H_z/cE_x = \mu_h H_z/c \text{ .}$$

The Hall mobility, μ_h, differs from the drift mobility, μ_D, because of collisions which make it necessary to employ a different averaging process. The usually accepted ratio is

(7) $$\mu_h/\mu_D = 3\pi/8 \ .$$

However, this ratio is seldom found to hold in actual measurements.

Solving equation (6) for E_y gives

(8) $$E_y = (\mu_h H_z/c)E_x \ .$$

But $E_x = J/\sigma$, where J is the current density and σ is the conductivity.

Thus

(9) $$E_y = (\pm\mu_h/c\sigma)H_z J = R_h H_z J$$

where the Hall coefficient R_h is defined as

(10) $$R_h \equiv \pm\mu_h/c\sigma = 1/n(\pm q)c$$

since $\sigma = n(\pm q)\mu_h$.

For a given current I the current density J is

(11) $$J = I/WT$$

where W is the width of the crystal in the Y direction and T is the thickness in the Z direction. The interpretation here that the smallest dimension of the crystal is usually in the direction of the magnetic field is correct.

Solving equation (9) for R_h gives

(12) $$R_h = WT\Delta V/WHI = T\Delta V/HI$$

since $\Delta V/W$ is E_y.

In laboratory or practical units (Volts, Amperes, coulombs, gauss, cm., gram, sec); the above equation becomes:

(13) $$R_L = 10^8 (\Delta V) T/IH$$

and since $\pm\mu_h = R_h c\sigma$

(14) $$\mu_L = |R_L| / \rho_L$$

the resistivity ρ_L can be determined from

(15) $$\rho_L = WT \Delta V_x / I \Delta X.$$

Finally then μ_L the Hall mobility in practical units can be determined from

$$\mu_L = \frac{10^8 \ (\Delta V) \ T}{I \ H \rho_L}$$

Procedure

The Magnetic Field. The magnet used for the Hall measurements and later for the Suhl-effect measurements was a military surplus radar magnet. The field in the gap was not uniform but was believed to be satisfactory as approximately 1 mm^3 of the gap was used and the variation in such a small volume was quite small.

Measurement of the field was made with the mounting board for the crystal removed. Test measurements of the field with the mounting board in place showed no change in the field due to its presence.

Initial measurements of the field with a General Electric fluxmeter of the meter deflection type showed variable readings. Field strengths of more than 4,000 gauss were found near the pole pieces, and the meter gave very inconsistent readings for fields this large. It was found that consistent results for the value of the magnetic field at the center of the gap could be obtained provided the fluxmeter was recalibrated after each measurement and the meter was not allowed to snap back to zero while in the field. The recalibration was effected by first setting the zero-set on the meter and then checking the calibration with a standard magnet providing a field of 2,500 gauss. If the meter reading was too great the fluxmeter was placed with reverse polarity in a field slightly greater than 5,000 gauss. If the meter reading was too small the fluxmeter was placed in the same magnetic field but with the polarity of the fluxmeter in the same direction as the field. Polarity of the fluxmeter was considered to be with the field when the meter was not pinned but read on scale while in the magnetic field. With the recalibration the fluxmeter consistently measured the field at the center of the gap as (3650) gauss.

As a check on the General Electric fluxmeter and the calibration magnets used, the field was measured with a military surplus, radar magnet, fluxmeter. Accuracy for this meter was claimed to be better than 1 per cent. This fluxmeter consistently read 3640 gauss as the value of the field.

Because the surplus fluxmeter readings may have represented the average field rather than the field at the center of the gap the value given by the General Electric meter was taken as the more accurate. It was estimated that the standard magnets were accurate to within 2 per cent. For this reason and since the two meters gave comparable values the field value used was 3650 gauss $\pm$ 3 per cent.

<u>Probe Contacts</u>. Probably the major difficulty in the work represented by this thesis was encountered in the making of metallic probe point contacts with crystal surfaces. A particular contact of this type may vary in stability from being noisy to being an open circuit. In the construction of point contact transistors a large part of the noise was removed by electrically forming the collector point contact. This was also tried in other tests without apparent success. Much of the difficulty in making stable contacts was attributed to the coating of the crystal surfaces with ceresin wax. It was noticed that probe contacts on crystals at higher temperatures had a tendency to become open. In an effort to increase the stability of such contacts the

pressure on the points was increased until the crystals were occasionally fratured. Also the points were resharpened after being relocated a few times. Nevertheless the problem of making stable probe contacts was never satisfactorily solved.

Determination of Resistivity. The resistivity of a material is

$$\rho \cong (A/I)(\Delta V/\Delta L)$$

where A is the cross sectional area, I is the total current through the cross section and $\Delta V/\Delta L$ is the potential gradient in the same direction as the current. Thus a determination of the cross sectional area and a determination of the potential gradient for a given value of current allowed the resistivity to be calculated.

The error in measuring the cross sectional area was probably about 2 per cent. The error in measuring the potential gradient was slightly greater than 1 per cent and the error involved in measuring the current was less than 1 per cent. Thus the estimated maximum error in determining the resistivity was 4 per cent. The importance of a homogeneous crystal accurately ground to exact dimensions was apparent.

Hall Voltage. The Hall mobility in laboratory units may be expressed by

$$\mu_h = \frac{10^8 (\Delta V_h) T}{IH\rho}$$

where ΔV_h is the transverse voltage produced by the Hall effect and T is the thickness of the crystal in the transverse direction.

Thus to find the Hall mobility it was only necessary to measure the transverse voltage as the other quantities had been previously determined. To accomplish this probes were placed in contact with the transverse crystal surfaces as nearly opposite from each other as possible. A photograph of the crystal mounting board and the voltage probes is shown in Plate VII, Fig. 2. The voltage differences between the probes was then measured with a K-2 potentiometer for currents in both longitudinal directions through the crystal and with the crystal in and out of the field. The current was reversed in preference to reversing the field because of the lesser probability of disturbing the probe point contacts. Voltage measurements with the crystal out of the field gave an indication of the alignment of the probes.

Data

Table 2. Measurement of thickness of crystal rod.

	Thickness of crystal rod (mm)
Side 1	1.077 $\pm$ .005
Opposite side	1.063 $\pm$ .005

Table 3. Measurement of width of crystal rod.

	Width of crystal rod (mm)
Side 2	1.014 $\pm$ .005
Opposite side	1.038 $\pm$ .005

Computed cross sectional area = 1.10 $\pm$ .02 mm^2.

Current through rod = 10 milliamp.

EXPLANATION OF PLATE VII

Fig. 1. Photograph of experimental arrangement used in determining Hall mobilities. Interconnecting wires are omitted to avoid confusion. Vacuum tube voltmeter was used only to find necessary range of operation of K-2 potentiometer.

Fig. 2. Photograph of crystal mounting board used in Hall and Suhl measurements. Point contact which is not spring loaded is emitter probe used to measuring Suhl angle.

PLATE VII

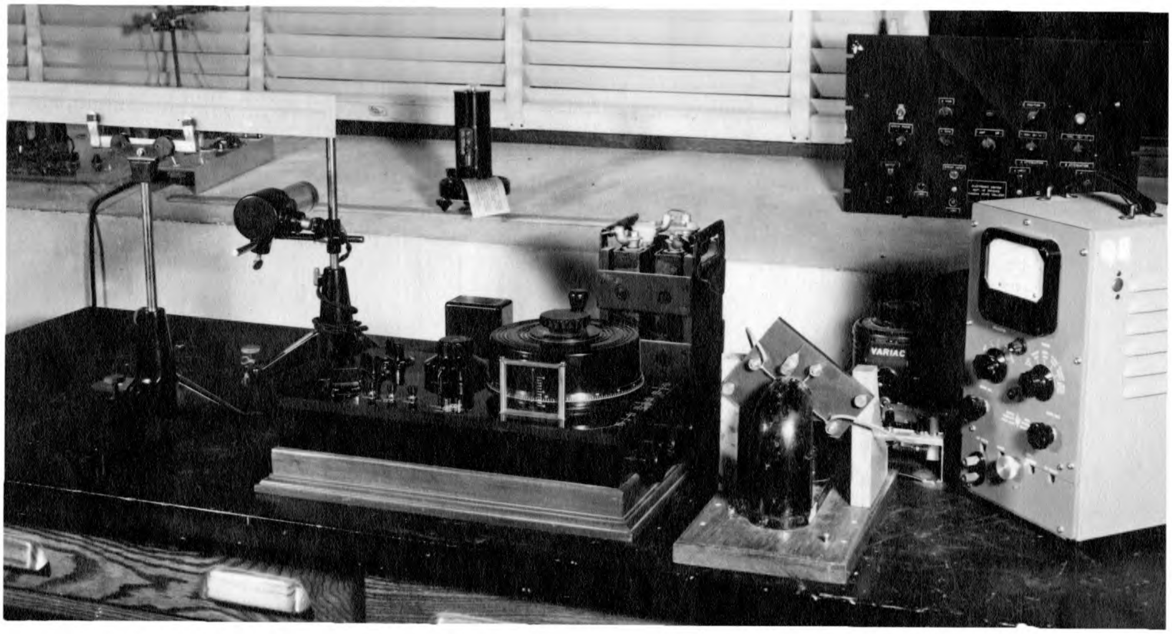


Fig. 1

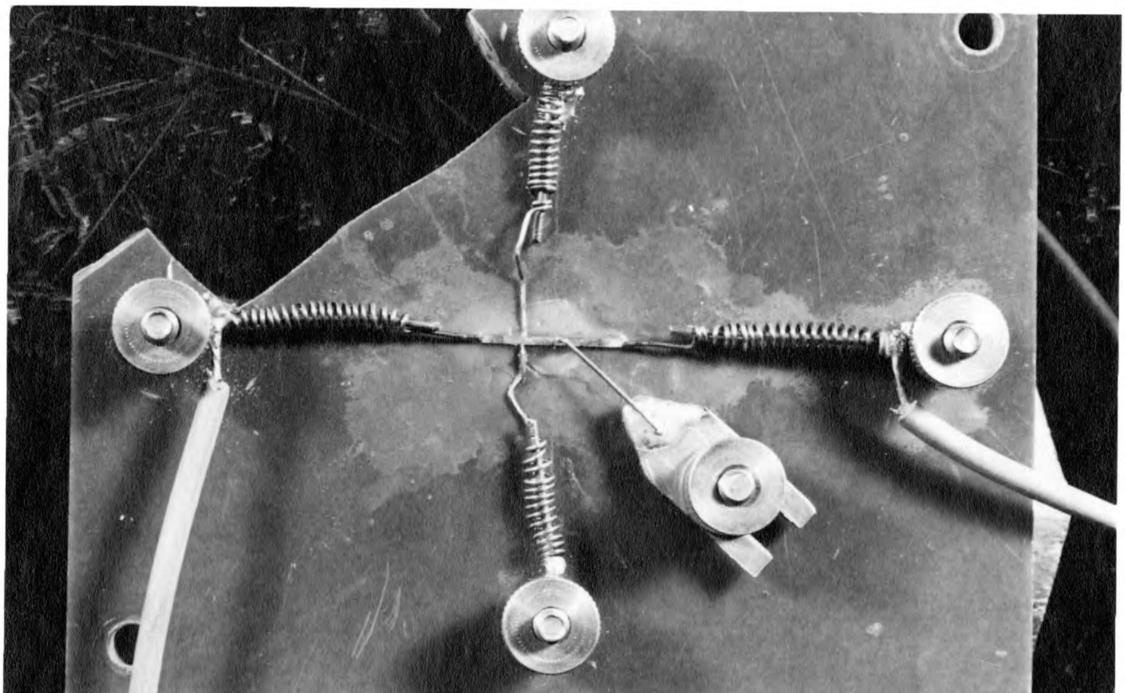


Fig. 2

Table 4. Measurements to determine potential gradient.

	V (volts)	L (mm)
1	1.70	2.712
2	1.70	2.712
3	3.82	6.025
4	3.85	6.135
5	3.84	6.078
Total	14.91	23.662

Computed potential gradient = .630 ± .002 volts/mm.

Computed resistivity for the p-type rod = 6.9 ± .3 ohm-cm.

Using a right hand coordinate set with the p-type germanium crystal rod having its long dimension in the X direction, the Hall voltages and polarities were as follows:

Table 5. Measurements of Hall voltage.

	Current in positive X direction Transverse field in the negative Y direction	Current in the negative X direction Transverse field in the positive Y direction
Magnetic field in the negative Z direction	$\Delta V = .07067$	$\Delta V = .07291$
	.06938	.06987
	.06874	.06969
	.06795	
No magnetic field	$\Delta V = .00323$	$\Delta V = .00406$
	.00320	.00303
	.00317	.00317

Average ΔV in magnetic field = .070 ± .002 volts.

Average ΔV with no magnetic field = .0033 ± .0002 volts.

As the transverse voltage produced without a magnetic field is in the same direction as the voltage in the field it must be subtracted from the average voltage produced in the field to find the voltage resulting from the Hall effect and not from the misalignment of the test probes.

Corrected ΔV = .067 ± .002 volts.

Calculated μ_h = 2800 cm^2/volt-sec with a maximum error of 12 per cent or 2800 ± 300 cm^2/volt-sec.

Calculated $\mu_D = 8\mu_h/3\pi$ = 2400 ± 300 cm^2/volt-sec.

Discussion of Results

The result for μ_D of 2400 ± 300 cm^2/volt-sec is to be compared with the usually accepted value of 1700, +500, -100 cm^2/volt-sec.

Since this result was rather large the equipment was reassembled to check all measurements. No significant variations from the original measurements were found.

Of considerable interest in discussing the results obtained is a report by Dunlap (4). According to this observer, in measurements obtained from about three hundred crystals mobility values of as high as 2540 cm^2/volt-sec were found for p-type crystals. In these measurements point contacts showed higher mobilities than plated contacts. In the report it was also pointed out that at room temperatures the apparent mobility often decreases with time. Finally it was concluded that only a lower limit exists for mobility as determined by the Hall effect.

As has been pointed out before the Hall mobility varies considerably from sample to sample. Therefore, even though the value of the Hall mobility was quite high in this measurement, it was not unreasonable.

SUHL EFFECT

The injection of minority carriers into a semiconductor rod placed in electric and magnetic fields causes the minority carriers to be deflected from the direction of the electric field. Majority carriers in the crystal set up a transverse voltage as a result of the Hall effect. The resultant electric field then that acts upon the minority carriers is in a different direction than the applied electric field. If the effect of the minority carriers is neglected the direction of the resultant electric field will be for small angles

$$\theta_p \cong E_y/E_x = \mu_{ph}(10^{-8})H$$

from the discussion of the Hall effect given on page 29.

The effect upon the minority carriers as a result of the magnetic field and the resultant electric field will be to deflect them through an additional angle

$$\theta_n = \mu_{nh}\ (10^{-8})\ H.$$

The total angle then between the path of the minority carriers and the applied electric field E_y will be

$$\theta = \theta_n + \theta_p = (\mu_{nh} + \mu_{ph})10^{-8}\ H.$$

Expressed in terms of the drift mobility this becomes

$$\theta = 3\pi/8\ (\mu_{nD} + \mu_{pD})10^{-8}\ H.$$

Using the usually accepted value for these quantities gives

$$\theta = 1.18\ (3600 + 1700)10^{-8}(3650) = 0.23 = 13^{\circ}.$$

Procedure

The experimental arrangement used for this measurement was similar to that used in the Hall effect measurement. The addition of a fifth point contact allowed the injection of electrons into the p-type crystal. For this work it was necessary to reverse the magnetic field. A photograph of the crystal mounting board with the emitter probe in place is shown in Plate VII, Fig. 2. Because of the electrical difference in the two collectors used the change in the collector current with the crystal in the magnetic field due to the change in emitter current was normalized by dividing by the change in each collector current with the crystal out of the magnetic field. The results were then plotted to determine the separation of the emitter and collector and hence the angle which produced the largest change in collector current for a given change in emitter current.

Data

I_2 and I_3 are the collector currents, I_4 the emitter current, and I_5 the longitudinal current through the crystal. X is the emitter-collector separation.

Table 6. Normalized changes in collector current for given change in emitter current.

X mm	H 3650 gauss	I_4 MA	I_2 MA	I_3 MA	ΔI_2 MA	ΔI_3 MA	$\Delta I_2/\Delta I_{23}$	$\Delta I_3/\Delta I_{32}$
		$I_5 = 7MA$						
Trial 1	+	0	8	26				
		4	2	46	6	-20	-1.00	1.18
1.0	0	0	9	28				
		4	15	45	-6	-17	--	--
	-	0	7	28				
		4	16	44	-9	-16	1.33	.94
	+	0	10	26				
		4	20	45	-10	-19	1.11	1.12
1.6	0	0	11	27				
		4	20	44	-9	-17	--	--
	-	0	10	27				
		4	20	44	-10	-17	1.11	1.00
	+	0	10	25				
		4	19	40	-9	-15	.9	1.07
0.4	0	0	10	26				
		4	20	40	-10	-14	--	--
	-	0	11	25				
		4	25	40	-14	-15	1.4	1.07
	+	0	11	26				
		4	19	46	-8	-20	.73	1.11
1.35	0	0	10	27				
		4	21	45	-11	-18	--	--
	-	0	10	27				
		4	26	42	-16	-15	1.46	.83

Table 6 (Cont').

X mm	H 3650 gauss	I_4 MA	I_2 MA	I_3 MA	ΔI_2 MA	ΔI_3 MA	$\Delta I_2/\Delta I_{23}$	$\Delta I_3/\Delta I_{32}$
	+	0	10	26				
		4	18	42	-8	-16	1	1
7.3	0	0	10	28				
		4	18	44	-8	-16	--	--
	-	0	11	27				
		4	20	43	-9	-16	1.12	1
Trial 2	+	0	22	12				
		4	33	30	+11	+18	.78	1.8
1.0	0	0	21	12				
		4	35	22	+14	+10	--	--
	-	0	20	12				
		4	38	20	+18	+8	1.29	.8
	+	0	21	12				
		4	35	32	14	20	.78	1.67
.83	0	0	22	12				
		4	40	24	18	12	--	--
	-	0	22	12				
		4	46	20	24	8	1.34	.67
	+	0	22	12				
			36	22	14	10	1	1.25
.64	0	0	22	12				
		4	36	20	14	8	--	--
	-	0	22	12				
		4	37	20	15	8	1.07	1

Table 6 (Concl.)

X mm	H 3650 gauss	I_4 MA	I_2 MA	I_3 MA	ΔI_2 MA	ΔI_3 MA	$\Delta I_2/\Delta I_{23}$	$\Delta I_3/\Delta I_{32}$
	+	0	22	12				
		4	36	26	14	14	1	1.4
1.1	0	0	22	12				
		4	36	22	14	10	--	--
	-	0	22	12				
			38	20	16	8	1.14	.8
	+	0	23	13				
		4	38	30	15	17	.83	1.7
2.3	0	0	22	12				
		4	40	22	18	10	--	--
	-	0	22	12				
		4	44	20	22	8	1.22	.8

Results

A graphical presentation of the results obtained for the two trials is shown on Plates VIII and IX. The resulting dip in the graph of trial 1 was not considered as accurate or significant but indicated a collector-emitter separation of 1 mm to be examined in trial 2.

In trial 2 the largest change in collector current for a given change in emitter current occurred at a collector-emitter separation of 0.9 mm. As the emitter was approximately in the center of the rod, and the rod was 1.07 mm thick, the experimentally determined angle was

$$\theta = .53/0.9 = .59 = 34^{\circ}.$$

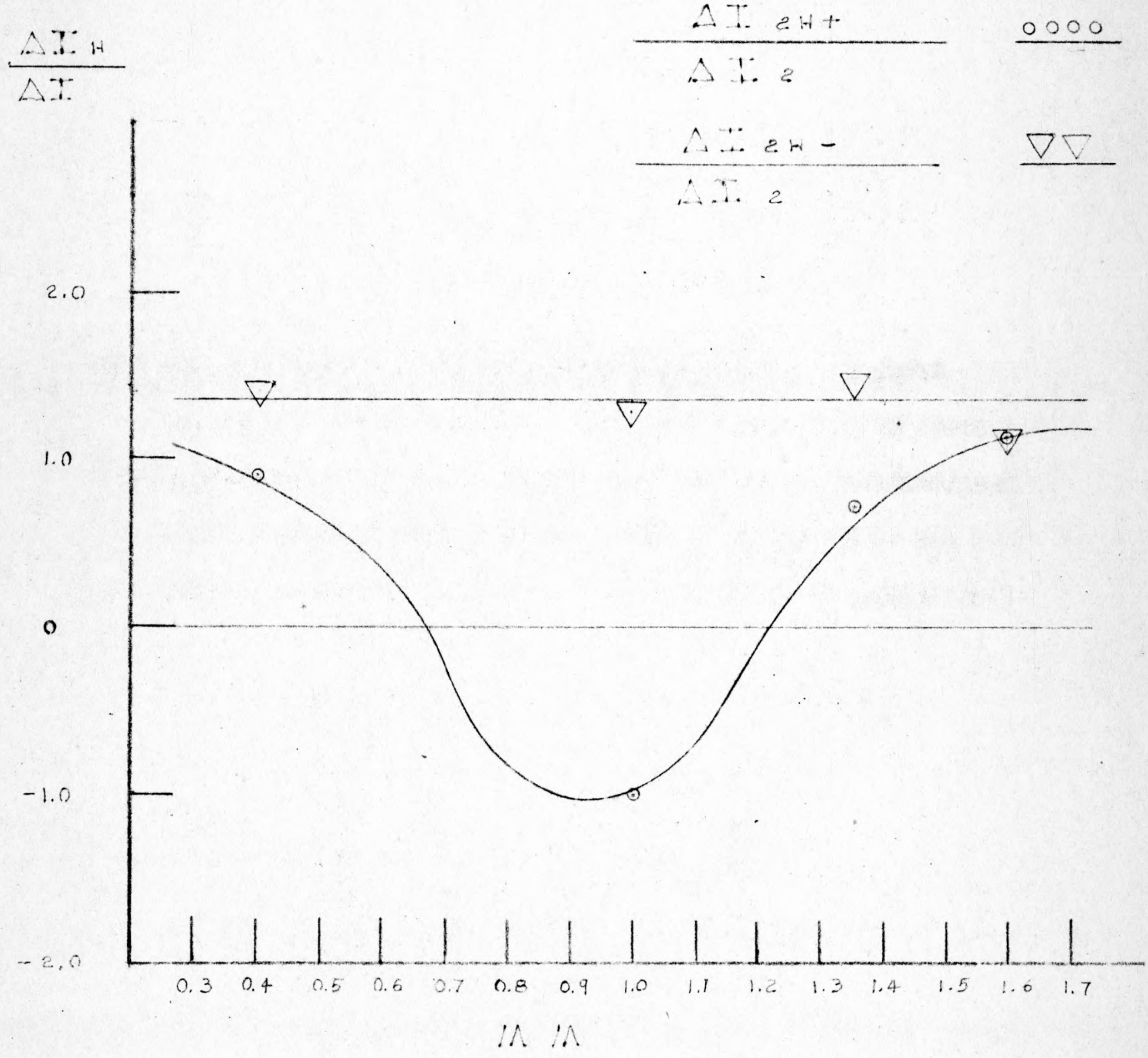
EXPLANATION OF PLATE VIII

Graph for trial I normalized values of the change in collector current in a magnetic field due to a change in emitter current vs longitudinal collector-emitter separation. Dip in graph at 0.9 mm was not considered significant but indicated separation to be investigated in trial II. Graph for trial II is shown on Plate IX.

PLATE VIII

TRIAL No I

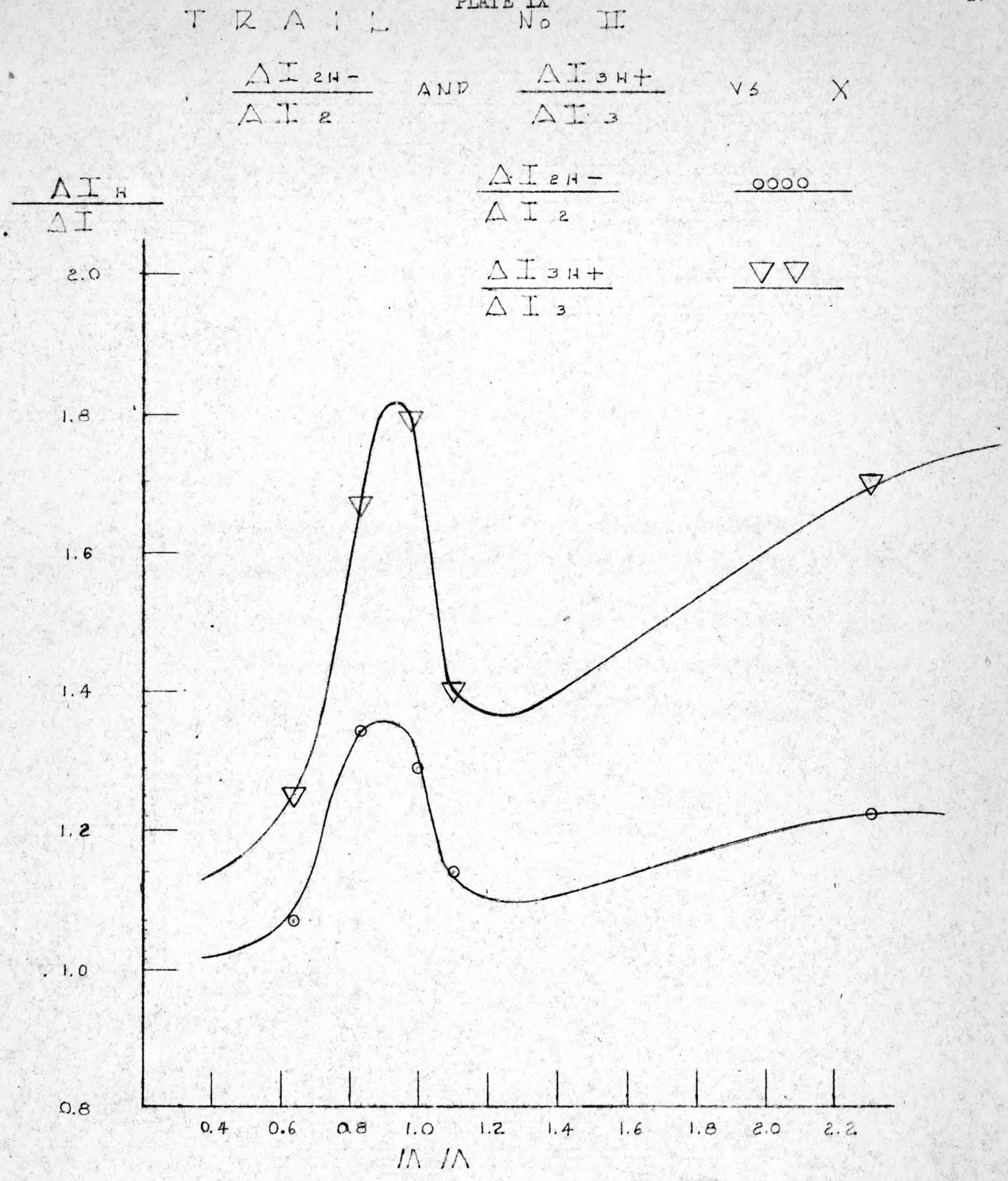
$\frac{\Delta I_{2H\pm}}{\Delta I_2}$ vs X



EXPLANATION OF PLATE IX

Graph for trial II of normalized values of the change in collector current in a magnetic field due to a change in emitter current vs longitudinal separation of collector and emitter. Graph shows reduction of collector point resistance when 0.9 mm from emitter due to surface concentration of minority carriers from Suhl effect.

PLATE IX


TRAIL No II
ΔI 2H- / ΔI 2 AND ΔI 3H+ / ΔI 3 VS X
ΔI H / ΔI
ΔI 2H- / ΔI 2 0000
ΔI 3H+ / ΔI 3 ▽▽
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
/Λ /Λ

Discussion of Results

The results obtained in the Suhl measurements were inconclusive. The experimental value of 34° was to be compared with the theoretical value of 13°. In order to check the results obtained the experiment was carried out using another method. This method consisted of placing the collector on a transverse side of the crystal and moving the emitter along the opposite side to determine the angle for change in collector current due to the emitter current. The results obtained by this method were not recorded as they were unreliable as a result of difficulty with the point contacts. Because of the difficulty of obtaining reliable results with the equipment used the Suhl measurements were not continued.

CONCLUSIONS AND SUMMARY OF THESIS

Procedure and results have been given for the construction of point contact transistors, measurement of drift mobility, measurement of Hall mobility, and in examination of the Suhl effect.

Two important problems have evolved from the work leading to this thesis. The amount and polarity of electrical forming seemed to be inconsistent and thus further examination of this factor would be desirable. Also the results obtained in the Suhl effect measurement were consistent but did not agree with theoretical predictions, therefore it would seem that the theory of this effect should be reconsidered.

Because of the difficulty in handling the small crystals used in these measurements, the type of laboratory work described in this thesis is suitable only for commercial or graduate purposes. However, with experimental arrangements previously put in order similar measurements might be made in advance electronic laboratories.

The results obtained in the measurements described in this thesis were considered to be as accurate as equipment and time would allow.

ACKNOWLEDGMENTS

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GERMANIUM IN ELECTRICAL CIRCUITS
AND ITS ELECTRICAL PROPERTIES

by

DARRELL DEAN McKIBBIN

B. A., Iowa State Teachers College, 1952

AN ABSTRACT OF A THESIS

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Department of Physics

KANSAS STATE COLLEGE
OF AGRICULTURE AND APPLIED SCIENCE

1956

The purpose of the work done in connection with this thesis was to examine some of the electrical characteristics of semiconductor materials and to construct and test as amplifiers point contact transistors of such materials.

Construction of several point contact transistors was carried out. These constructed transistors were tested for voltage gain in a particular circuit. Voltage gains as high as 125 times without noticeable distortion were obtained.

The drift mobility for holes in n-type germanium crystals was measured. The value obtained for the mobility was 1700 $\pm$ 100 cm^2/volt-sec. This agreed quite well with the accepted value of 1700 $\pm$ 90 cm^2/volt-sec.

The Hall mobility for holes in p-type crystals was measured. The result obtained of 2800 $\pm$ 300 cm^2/volt-sec did not agree with the usually accepted value of 2000, + 500, -100 cm^2/volt-sec. However, the results obtained did agree with those reported by another observer. The value obtained for the Hall mobility by Dunlap[1] was 3000 cm^2/volt-sec.

The angle of deflection of minority carriers in a p-type crystal due to the Suhl effect was measured. The experimental angle determined was 34° which was to be compared with the theoretical angle of 13°. No explanation of the lack of agreement of the experimental and theoretical values was found.

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