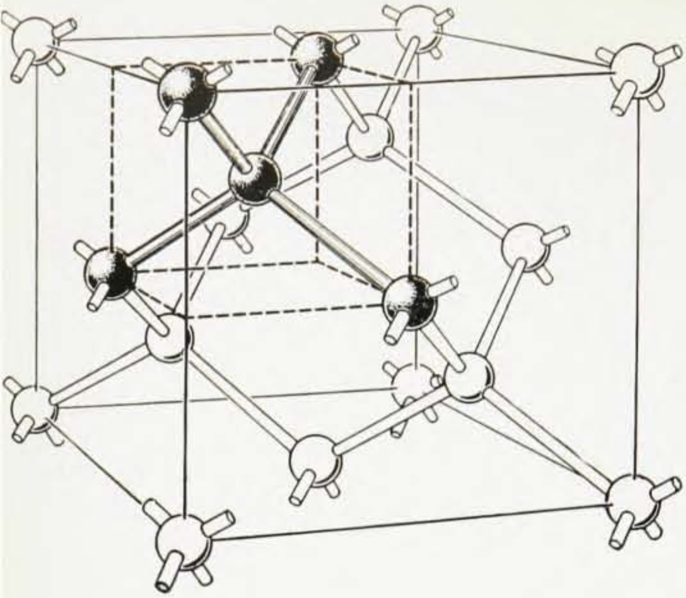


Germanium, the crystal of the transistor, has the crystal structure of diamond. *(Illustration courtesy Bell System Technical Journal, July, 1949, p. 338.)*

Holes and Electrons

by ***William Shockley***

Some new experiments in transistor electronics are described here in which concepts suggested by theory have been verified directly by experiment.

Recently a far more intimate and detailed view of the basic processes by which electrons carry current has been made possible by new experiments based upon the invention of the transistor.

Electronic conduction, in which only the electrons move while the atoms or ions remain in fixed positions, is preferred in most electrical applications since it does not cause the gross chemical or physical changes produced by ionic conduction. Aside from their intrinsic usefulness, the new experiments provide another example of the intimate connection between the basic and the applied in science, for here fundamental scientific knowledge, which has stimulated technological developments, has in turn been helped directly by the developments it stimulated.

The transistor was invented by J. Bardeen and W. H. Brattain of the Bell Telephone Laboratories. They showed that when two rectifying contacts, in close proximity to one another, are made to a germanium crystal, the electronic structure in the germanium may be changed by passing current forward through one of the points, and that this change may be detected by drawing reverse current through the other point. The effects are so pronounced that, as is well known now, power gain may result and the device may be used as an amplifier or for many of the other purposes for which a vacuum tube is usually employed. The description of the transistor as a useful circuit element has been given so many times that I shall not repeat it here (see, for example, *Physics Today* for August, 1948, page 22), but work on this device has made possible descriptive experiments on various phases of electronic conduction. These experiments have experimentally supported parts of the physical picture of electronic conduction which were based previously on theoretical considerations alone.

This paper was the subject of the 19th Joseph Henry Lecture delivered before the Philosophical Society of Washington on May 13, 1950. It presents in a simplified form a portion of the author's book "Electrons and Holes in Semiconductors, with Applications to Transistor Electronics" which is planned for publication this fall as one of the Bell Telephone Laboratories Series. *William Shockley* acquired his interest in solid state physics at MIT while carrying out his doctorate research under J. C. Slater. He has continued in this field at Bell Telephone Laboratories except for interruptions for war work. At the end of World War II, the Solid State Group at Bell Telephone Laboratories was organized with Dr. Shockley as a cosupervisor. Special emphasis was placed on semiconductor research because of the possibility of making amplifiers, an aim which was achieved with the transistor and which led to the experiments in transistor electronics described in this article.

The physical picture of electronic conduction resulting from investigations of silicon and germanium in connection with the development of crystal rectifiers during the war, and still earlier theories, describes the conduction process in considerable detail. Prior to the new experiments (and I shall consider only germanium for which the story is most complete) only certain over-all conclusions from the theory could be verified directly. In P. W. Bridgman's sense of the word "operational" there were many conceptual aspects of the picture which had no operational verification. The new experiments give a real operational meaning to a large number of the concepts which formerly entered only as intermediate steps in the calculations before theory was compared with experiment. In addition to giving this deeper and more intimate insight into the basic mechanisms the new results furnish information of direct applicability in problems of understanding and designing transistor devices.

The Physical Picture

Like carbon, germanium is tetravalent and crystallizes in the diamond structure, in which each atom is surrounded by four neighbors with which it forms electron-pair bonds, all making equal angles with each other. The valence-bond system may be regarded as a rigid structure which holds the atoms in place and provides a role for each of the four valence electrons of the germanium atoms. Since the electrons are occupying all of the possible bond wave functions, there is no possibility of producing current by displacing them while keeping the valence-bond structure intact.

If a germanium crystal or a diamond crystal is illuminated by light with sufficiently energetic photons, then the valence-bond structure may be temporarily disturbed. A high energy photon will eject an electron from one of the bonds and this electron will then be free to move about the crystal. The hole left behind can also move since electrons in adjoining bonds may move into it, thus producing a net displacement of the hole.

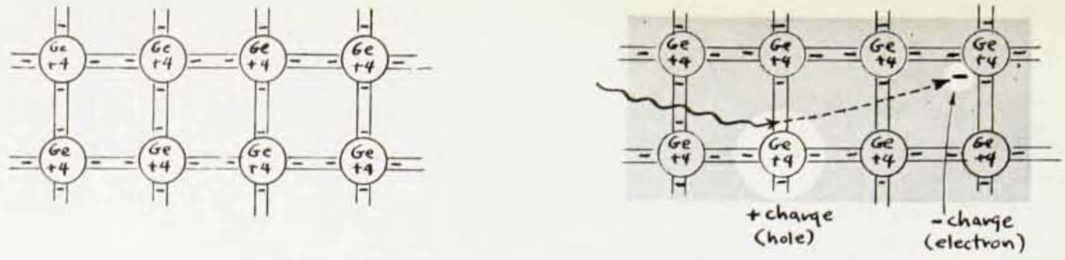
According to the accepted theoretical pictures the excess electron in a semiconductor, or simply the electron, as it is usually called, can be thought of as behaving much like an electron in free space. It can move through the crystal lattice for great distances without being appreciably deflected by the fields due to the atoms of the lattice. The reason that it is not deflected each time it travels through a unit cell is that it moves as a wave. If the crystal were perfectly periodic, this wave could travel indefinitely without being scattered; but after traveling a few thousand lattice constants the electron is almost certain to be scattered in germanium at room temperature because thermal vibrations disturb the perfectly periodic arrangement of the atoms.

Precisely similar theoretical conclusions are reached about the behavior of a hole. Thus the physical picture of an electron is that of a more or less localized wave packet having minus one electronic unit of charge which moves in a random fashion under the influence of thermal agitation and changes its direction of motion, on the average, each time it has traveled about one thousand lattice constants. The picture of the behavior of a hole is precisely the same except that the change is plus one electronic charge. (This is not an obvious result and can be justified only by lengthy theoretical arguments.)

Expected Effects

It should be pointed out that other types of behavior are perfectly conceivable. For example, it might be possible that the effect of light falling upon the crystal would be to destroy entirely one electron-pair bond. Under these conditions the hole would have a charge of + 2 electronic units and would otherwise behave the same as the hole, as we have already described. Thus, one objective of experiment is to verify that the charges which move in the crystal are − 1 and + 1 electronic units of charge respectively. Another objective of experiment is to show that the random diffusive motion actually takes place.

Other effects must be consistent with the physical picture. Under the influence of an electric field a steady drift is superimposed on the random motions and as a result, in addition to diffusing away from any given point, an electron tends to flow through the crystal in a direction opposite to the electric field—opposite since its charge is negative. Similarly a hole tends to flow in the direction of the applied field. The localized disturbance of the valence electrons, which is what the hole really is, moves just as would a particle and drifts in the direction of an applied field. This displacement of the disturbance in the direction of the applied field



Conduction in the perfectly bonded structure may be produced by photon absorption which produces hole-electron pairs.

has been directly observed as a result of experiments on transistor action. If both electric and magnetic fields are simultaneously present then the drift motion produced by the electric field results in a sidewise thrust in the presence of the magnetic field.

It is interesting and important to note that the same electric and magnetic fields will exert a side thrust on holes and electrons in the same direction rather than in opposite directions. This can be understood by realizing that the force due to motion in a magnetic field is dependent both upon the direction of motion and upon the charge. For the case of an electron the motion is opposite to that of a hole and the sign of the charge is also opposite. As a result the sidethrust of the magnetic field is in the same direction for both carriers. There are, of course, deflections due to the random motion as well as the steady drifting motion of the particles, but these cancel out on the average so that for purposes of calculating the deflection it suffices to consider the average motion. One of the new experiments shows that these sidewise deflections actually occur, and under favorable conditions result in concentrating both holes and electrons on one side of a conductor.

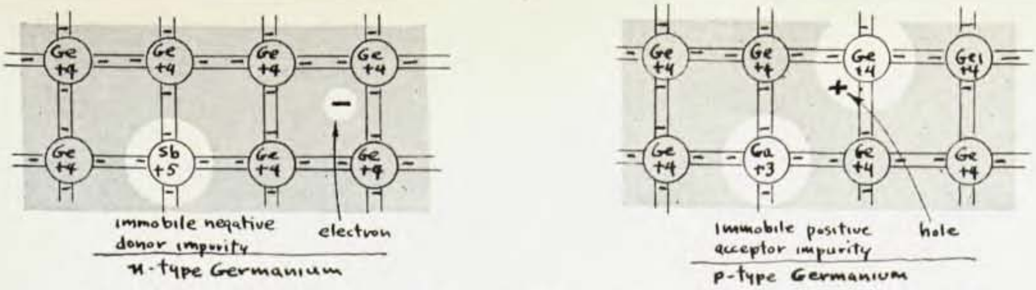
A Fortunate Property

In germanium at room temperature holes and electrons are created by other processes than light absorption. Thermal agitation of the lattice causes the spontaneous breaking of bonds and the generation of holes and electrons. The reciprocal process goes on at a compensating rate under conditions of thermal equilibrium so that hole electron pairs are being continually created and recombined. In germanium at room temperature these processes would reach a balance when the concentration of holes and electrons is sufficient to give the sample a resistivity of approximately 60 ohm cm.

If it were necessary to deal exclusively with semiconductors having equal numbers of holes and electrons, the problem of unraveling the behavior of the individual types of current carriers would be much more difficult. Fortunately, samples having conductivity by electrons alone or by holes alone can be prepared in controlled ways.

A specimen which conducts by electrons alone is called n-type since the current carriers are negative. Its conductivity arises from the presence of chemical impurities called donors which give electrons to the conduction band. A typical donor atom for germanium is antimony which has a valence of 5. This atom forms four electron-pair bonds with its neighbors using for this purpose four of its five valence electrons. The fifth valence electron cannot fit into the bond structure and becomes free to wander through the crystal. The addition of antimony does not produce a net negative charge in the crystal, however, because the antimony atom itself represents a fixed immobile positive charge, its share of the four valence bonds around it being insufficient to neutralize the charge of + 5 units on its core. At low temperatures the attraction between this plus charge and the electron is sufficient to bind the electron to the antimony ion in a wave function similar to that of an electron in a hydrogen atom. The binding is much weaker than that of hydrogen, however, because the charge of the antimony ion is imbedded in a dielectric consisting of the germanium atoms, and as a result the electron is so weakly bound that thermal agitation readily frees it. At room temperature, in a sample of n-type germanium, a negligible number of electrons are bound to the donor ions.

An entirely similar situation occurs for a sample containing impurity of valence 3, of which gallium is an example. In such a crystal the electron-pair bonds around the gallium atom are completed by the stealing of an electron from an electron-pair bond somewhere else. This results in the presence



Adding donors with valence 5 produces an n-type semiconductor with conduction by electrons alone. Acceptors with valence 3 similarly produce p-type with conduction by holes.

of a mobile hole, and the gallium atom with its surrounding share of the valence bonds becomes a negative ion. Because of its thieving nature an atom of valence 3 is politely called an acceptor.

If both acceptors and donors are incorporated in germanium in equal numbers, the resulting conductivity is not the sum of the conductivities of the two types but is substantially the same as it would be if neither were present. The reason is that the electrons produced by the donors combine with the holes produced by the acceptors until finally an equilibrium density of holes and electrons is produced just equal to that which would occur as a result of spontaneous thermal generation. Consequently, the conductivity of a sample having donors and acceptors is determined by the more abundant type of impurity and is the same as it would be if simply the excess density of that type alone were present.

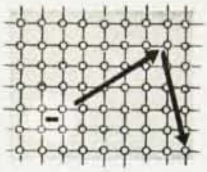
The basis of the development of transistor electronics at Bell Telephone Laboratories both from the applied and theoretical sides has been the preparation by J. H. Scaff and his colleagues of germanium of high purity with controlled additions of donors and acceptors. Another vital aid to research has been the growth by G. K. Teal of relatively large and perfect single crystals. And still another essential ingredient has been the development by W. L. Bond and G. L. Pearson of microtechniques for adjusting point contacts and cutting small specimens or filaments.

We may summarize the physical picture of the principal attributes of holes and electrons as follows: they behave like particles having charges equal respectively to minus the charge of the electron and plus the charge of the electron. They undergo random thermal motions so that they tend to diffuse away from any point where they are initially located. Under the influence of an electric field an electron drifts opposite to the field and a hole with the field. These drift velocities are, according to theory, proportional to the electric field, the proportionality constant being called the mobility. According to convention, mobility is always given as a positive number so that it gives merely the ratio of speed to electric field and is plus for electrons as well as for holes. Under the influence of electric and magnetic fields both electrons and holes tend to be thrust towards the same side of the specimen. The physical picture also includes the concepts of electron and hole densities usually expressed in number per cubic centimeter and written as n and p.

Conductivity and Hall Effect

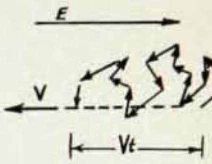
The pretransistor measurements of the behavior of holes and electrons consisted chiefly of measurements of conductivity and Hall effect. Conductivity was measured simply by preparing a specimen of suitable shape, preferably with a rectangular or circular cross section and much longer than it was wide. Current was then passed through this specimen and the conductivity measured using Ohm's law. For an n-type sample of germanium this conductivity gave information about the product only of three of the quantities of the physical picture: the size of the charge, the density of electrons, and their mobility. By itself it verified nothing about sign of the charge of the carrier since the theory requires that the charge and the direction of motion are coupled so that ordinary positive resistances occur.

The other measurement which gave information on the nature of the conduction process was based on the Hall effect. When electrons flow down a filament in the presence of electric and magnetic fields, they tend to be deflected to one side. As a result of this deflection there is a small accumulation of electrons on one side of the specimen and a corresponding deficit on the other side. These charges produce an additional electric field which



The excess electron wave pocket moves many lattice constants between deflections. The resultant motion is diffusive.

An electric field superimposes a drifting motion with average velocity V on top of the random motion. The ratio V/E is the mobility μ.



tends to neutralize the sidewise thrust of the magnetic field. According to one somewhat oversimplified way of considering the Hall effect, the steady state is reached when the transverse electric field due to the accumulation of charge sets up a sidewise thrust which exactly balances the sidewise thrust due to the magnetic field.

It is evident that these sidewise electrical thrusts, which exert forces in the same direction for holes as for electrons, must correspond to fields of opposite signs when the carriers are considered separately. The same result can be seen by considering the transient effect which occurs when the magnetic field is being applied. As the magnetic field builds up, electrons in an n-type sample would be deflected towards the top; and in a p-type sample holes would similarly be deflected towards the top so that the transverse electric fields, which can be measured in Hall effect experiments, would have opposite signs for n-type and p-type. This difference in sign allowed the conductivity type to be determined by the Hall effect.

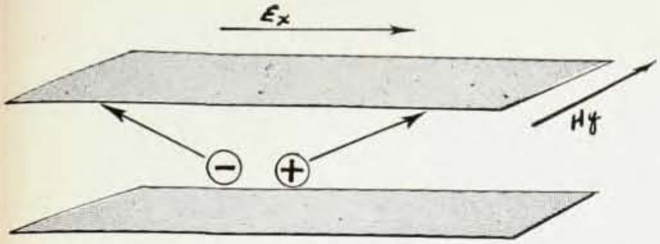
Furthermore, by equating the two thrusts it was found that a measurement of the ratio of transverse and longitudinal and electric fields at a known magnetic field is equivalent to a measurement of the mobility. This ratio of transverse to longitudinal electric fields is the angle in radians between the direction in which the current flows and the direction of the resultant or total electric field. In terms of a more detailed picture of the statistics of the process involved this angle has an interesting interpretation: if the electron were moving in a magnetic field alone, its path would be an arc of a circle. The Hall angle is the average angle of the arc between collisions.

So the Hall effect may be considered as a means of measuring mobility. Actually it is a very indirect means since it does not involve measuring times and distances in order to determine the drift velocities associated with the mobility. Time enters the mobility deduced from the Hall effect through the calibration of the instruments which measure the magnetic field. This indirectness has a theoretical counterpart as well, arising from the neglect of momentum transfer during collisions with the atoms; thus theory indicates that only under very special conditions can the mobility deduced from the Hall effect be considered as equivalent to the true or drift mobility. For germanium it appears at present that these simplifying assumptions are almost but not exactly correct. In principle, however, it is possible to have electrons and holes behave in such anomalous ways that the Hall effect gives the wrong sign.

Thus, from the operational viewpoint, the Hall effect cannot be regarded as giving a demonstration that particles drift with the predicted velocities nor does it show that they are deflected by the sidewise thrust as predicted by the physical picture. Practically, however, there is evidence that the Hall effect is generally reliable and most of the quantitative aspects of the theory are based on its use. Even accepting the mobility as given by the Hall effect, however, data from it and from the conductivity measurement give only two relationships among three quantities (the charge of the carrier, the density of the carriers, and the mobility).

Radioactive Antimony

The concentrations of donors and acceptors which produce the conductivities usually observed in germanium samples are extremely small, of the order of one atom in one hundred million, so small that conventional chemical methods of analysis are quite inadequate. If the impurity contains a radioactive isotope, however, even these small concentrations may be measured. Samples of germanium containing radioactive antimony have been studied by Pearson, Struthers, and Theuerer and the effective concentration of added donor atoms has been directly determined. On the basis of the theoretical picture, the concentration of donors should be equal to the concentration of excess electrons so that in these

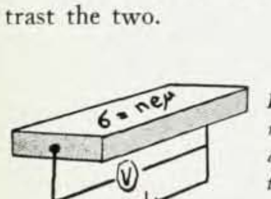


The drift velocity of electrons and holes is deflected upwards (+Z) by electric field E_x and magnetic field H_y.

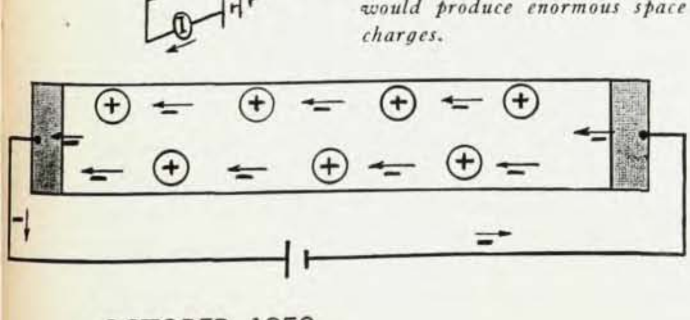
samples we may consider that the concentration is known. Even if no antimony is deliberately added, some impurity is always present and this must be estimated by control experiments. Combining this information with the knowledge of the mobility obtained from the Hall effect one is able to deduce an effective charge for the electron. This charge appears to be somewhat greater than the charge of the free electron but the accuracy of the data does not, at present, warrant a positive conclusion on this point. From the theoretical point of view as discussed above, the mobility of the particles and a correction factor may have to be introduced. Fortunately, the charge of the carriers can now be determined by a more direct means.

The Sign of the Charge—Carrier Injection

One of the basic new phenomena resulting from the transistor studies is that of hole injection. The phenomenon occurs when a point contact is made to a sample of n-type germanium. (A corresponding process of electron injection occurs when p-type germanium is used and the two types are grouped together under the phrase "carrier injection".) This process is so different from that occurring in ordinary conduction process that it is helpful to give first a description of the ordinary conduction process in more detail than usual in order to contrast the two.



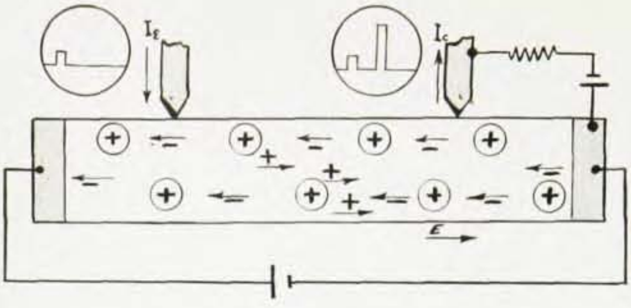
In an n-type semiconductor normal conduction corresponds to an incompressible flow of electrons since any accumulation would produce enormous space charges.



If electrodes are placed on the two ends of an n-type sample, and suitable precautions are taken to make them nonrectifying, then the passage of current through the sample involves a flow of electrons in at one of the terminals and out at the other. The total number of electrons in the sample stays constant during the process, however, because if any appreciable deviation in the total number of electrons occurred, the specimen would become electrically charged, and a very small fractional deviation would set up enormous electric fields. Thus the electron flow is like that of an incompressible fluid.

Another important feature of the ordinary conduction process is that the velocity of an electrical signal down a long wire of germanium is much greater than the velocity with which the electrons drift down the wire. If a coaxial line were made with a central conductor of germanium, for example, and a negative voltage were suddenly applied to one end, electrons would flow into that end almost instantaneously. This flow would produce an electric field which would be transmitted down the coaxial conductor with approximately the speed of light. This electric field would set in motion electrons at successively more distant points along the filament so that very quickly all of the electrons in the filament would be drifting in the same direction. It would not be necessary to wait until electrons injected at one end drifted to another point in the filament to detect the signal produced by applying the voltage.

The phenomenon of hole injection stands in great contrast to that of ordinary conduction. It is necessary to wait until the holes drift to another point to detect the signal. In the case of hole injection, a rectifying contact (of transistor emitter type) is made to the n-type germanium. When this rectifying contact carries a positive current into the germanium, the electronic equilibrium is upset. The reason is that the electrons drawn out of the germanium, when the positive current flows through the contact, are taken from the valence bonds rather than from the excess electrons of the conduction band. The theory for this behavior can be understood in terms of transistor action; for our purposes we may consider it simply as an established fact.



A pulse of holes injected by an emitter point is neutralized by extra electrons flowing in at the end terminals. The hole pulse drifts in the direction of the applied field.

Assuming that this process occurs, we see that when the point is positive, it generates holes within the germanium which can then diffuse away from the contact. If an electric field is present these holes will be carried away in the direction of the electric field.

Another point contact is made to the same sample and is biased in the negative direction, which is the reverse or high resistance direction for n-type germanium. If holes injected by the first point arrive at the second point, the high resistance of second point will be greatly reduced—this being one of the important transistor principles. Thus the second or collector point is a detector for holes and can be used to time the arrival of holes after they have been injected by the emitter point.

J. R. Haynes has used these effects to make precision measurements of the drift mobilities of holes and electrons: a thin rod of n-type germanium is caused to carry a steady current from end to end by large inert electrodes which do not inject holes; two point contacts are made to the rod and a pulse of holes is injected into the rod by one of the points; the other point is connected to an oscilloscope and the arrival of holes added is detected by a change in its reverse current. As soon as the emitter current flows a signal is detected at the collector, this being the ordinary Ohm law signal, discussed above, which is transmitted with the speed of light. It serves the useful purpose of giving a reference time to tell when the holes were injected. At an appreciable time later there is another signal on the collector point, which shows the arrival of the holes.

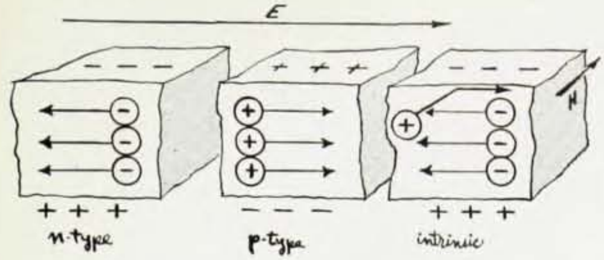
Haynes has found that the disturbance set up at the emitter point moves in the direction expected for a positive charge and that its drift velocity is proportional to the electric field. This experiment thus observes directly the drift velocity, which was a concept in the original theory not supported directly by experiment, and it also verifies the fact that the disturbance introduced has a positive sign. He has carried out similar experiments for p-type germanium into which electrons are injected.

A hole injected in these experiments will combine with an electron unless it is drawn out of the end of the filament first. Experiments using filaments with different cross sections show that this recombination takes place largely on the surface of the filament and is describable in terms of an average lifetime for a hole. Values ranging from less than one to over one hundred microseconds have been measured for both holes and electrons.

Unlike the case of ordinary conduction, electrostatic neutrality does not limit the number of holes which can be injected into a sample of n-type germanium. The reason is that as the holes are injected, they set up an electric field which attracts electrons. There is a practically unlimited supply of these electrons available to flow in through wires connecting the end terminals of the germanium sample to the battery, which is used for injecting the holes. Thus, very large concentrations of holes and electrons may be produced. The presence of the added holes and electrons under these conditions increases the conductivity of the sample and this increase can be used to measure the added concentration. The resulting conductivity modulation can be used so as to obtain power gain. Transistors using this principle, called filamentary transitors, have been shown by Pearson and Shockley to operate in accordance with the theory based on the physical picture and have been used to study some of the quantities entering the theory.

An Observation of Diffusion

An experiment which measures not the drift velocity in an applied electric field but measures instead simply the diffusion of added holes has been carried out by Goucher. No sweeping field is applied to the specimen and the emitter point is replaced by a small spot of light. (Goucher has shown by an independent experiment that every photon absorbed in the germanium over a wavelength range of 1.0 to 1.8 microns generates one hole-electron pair.) Since no net current is produced when hole-electron pairs are generated by the light, the electric fields



In the Hall effect, charges build up until the transverse field causes the current flow to run parallel to the specimen. In the Suhl effect, which requires strong electric and magnetic fields, concentration of carriers occurs since space charge neutralization of opposite types takes place: the case shown corresponds to injecting a few holes in an n-type specimen.

are so small that they contribute negligibly to the motion of the holes; and the holes thus move substantially under the influence of diffusion alone.

For such a case the manner in which the density of holes decreases at distances from the light source can be predicted directly from theory. The lifetime of a hole, which enters the calculation, has been determined by experiments of the sort carried out by Haynes. The presence of the holes can be detected by the collector point on the filament without drawing any current because when the holes arrive at this collector point they cause an internal contact potential difference to develop. By these means Goucher has detected the presence of holes which have diffused more than one millimeter away from the light source and has found that the hole density depends on distance from the light source in precisely the way one would expect, based on the picture of diffusion discussed above.

An Observation of Magnetic Deflection— The Suhl Effect

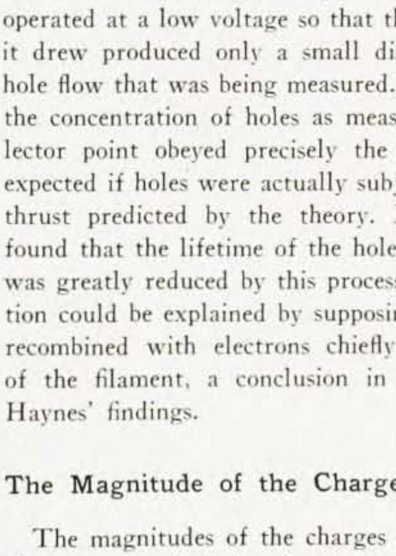
Direct evidence that holes and electrons are deflected by combined electric and magnetic fields in the predicted directions has been obtained by H. Suhl. In his experiment both holes and electrons are simultaneously present. This condition is very different from that occurring when holes and electrons are present individually. In the normal Hall effect, for one type of carrier alone, the carriers flow down the filament producing a current which is uniform across the cross section and the carriers have a uniform density. The uniform density is required by the fact that deviations from it produce a net space charge.

The Suhl effect is probably most easily described in terms of an extreme case corresponding to an intrinsic semiconductor (one in which holes and electrons are present in equal numbers). Here the combined action of electric and magnetic fields will tend to push the holes and the electrons both towards the same side. If the electric and magnetic fields are both sufficiently large, a situation made possible by germanium filament techniques, the holes and electrons may be concentrated on one side of the filament. Since the carriers are equally abundant, the combined densities of holes and electrons will produce no net space charge.

In Suhl's experiment only small concentrations of holes were injected into an n-type filament. These small hole currents were then found to be deflected by the magnetic field so that the holes were found all on one side of the filament. The means of detection was again a collector point operated at a low voltage so that the current which it drew produced only a small disturbance in the hole flow that was being measured. Suhl found that the concentration of holes as measured by the collector point obeyed precisely the theoretical laws expected if holes were actually subjected to the side thrust predicted by the theory. Furthermore, he found that the lifetime of the holes in the filament was greatly reduced by this process and this reduction could be explained by supposing that the holes recombined with electrons chiefly on the surface of the filament, a conclusion in agreement with Haynes' findings.

The Magnitude of the Charge—Rectification

The magnitudes of the charges of the holes and electrons can both be shown to be equal to the



The rectification curve for a p-n junction fits well if the carriers are assumed to have the charge of one electron and badly if another charge, such as 2e, is assumed.

electronic charge by studying the rectification curves of p-n junctions. A p-n junction occurs when the donor and acceptor densities vary in a single piece of germanium so that one part where the donors predominate is n-type while another part is p-type. A rectifier may be made by making low resistance contacts to the p- and n-parts, making such contacts being somewhat of an art.

Current flow across the junction between the p- and n-type parts has a very nonlinear current voltage relationship. The easy direction of current flow is that in which the p-side is biased positive so that holes tend to flow from it into the n-side while electrons flow in the opposite direction and on both sides of the junction carrier injection occurs. The behavior of holes and electrons in such junctions has been analysed and it is found that the theoretical relationship between current and voltage is the same as the theoretical formula for other types of rectifiers.

However, the greater perfection of the junctions made in germanium leads to a much closer approach of the experimental curve to the theoretical curve than has been observed before. The formula for rectification involves directly the effective charge of the carriers and it is found that the formula is best fitted for a p-n junction of high perfection by choosing the charge on the mobile carriers as that of the electron.

The quantitative fit of Suhl effect data also indicates that the charge is one electronic unit, but the available data are not so accurate as that for p-n junctions and the theory somewhat more involved.

Conclusions

Although the experiments just described have verified many features of the physical picture of the behavior of holes and electrons, the picture itself is not complete. The verified features, however, are those which are of most importance in practical applications. Applications in transistor electronics require knowledge of mobilities, drift velocities, diffusion, the magnitude of the charge, and the deflections of magnetic fields. These quantities have now been given an operational meaning (in Bridgman's sense) in situations closely resembling those in which they will be used for design purposes. For this reason these features of the physical picture have a reality which can hardly be affected by any future changes in the theory.

There are other aspects of the theory that have had some degree of test. The velocity distribution of the electrons is predictable and has been investigated theoretically through its influence on the scattering process. A more serious problem has to do with whether the electron waves move through the crystal like pressure waves in a gas, which can be only longitudinal, or like mechanical waves in a solid which have three sound velocities, this latter case corresponding to a degenerate state at the edge of the band. The increase in resistance in magnetic fields seems to require the more complicated case but the details have not yet been worked out. Even with these lacks, however, germanium has become one of the best understood of all electronic conductors and may well become the best understood as a result of studies centered around its application in transistor electronics.

In the pretransistor experiments only conductivity and Hall effect were measured giving two relations among three quantities (or among four quantities if μ and μ_H are distinguished). The new experiments give direct operational significance to all the remaining quantities of the table.