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P-N JUNCTION THEORY
and
THE JUNCTION TRANSISTOR

by
W. J. Leivo

OKLAHOMA STATE UNIVERSITY

June 1958

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Professor Leivo was introduced by
H. J. Stein

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P-N JUNCTION THEORY AND THE JUNCTION TRANSISTOR

by

W. J. Leivo, Professor of Physics
Oklahoma State College

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INTRODUCTION OF THE SPEAKER
by H. J. Stein

We have with us today from the Oklahoma State University, Dr. W. J. Leivo. In addition to Dr. Leivo's teaching assignments at the University, he is also carrying out research on semiconducting diamond, investigating the electrical and the optical properties. Prior to his coming to Oklahoma State he was with the Physics Department at Carnegie Institute of Technology. While at the Institute he was carrying on research in alkali halides. Part of the alkali-halide work was sponsored by the Atomic Energy Commission. The diamond work which he is doing now is sponsored by the Air Force. Dr. Leivo will talk today on the P-N junction theory and the junction transistor.

P-N JUNCTION THEORY AND THE JUNCTION TRANSISTOR

Lecture of 8 August 1957

by W. J. Leivo

The solid state physicists present here today, I understand, are in the minority, so I must ask that the minority group bear with me if I return to basic principles throughout my remarks.

When we consider a free atom such as the hydrogen atom, we know that there are different energy states for the electron in the atom. On an energy diagram the energy can be represented by lines indicating the energy level of the electrons in the atom corresponding, for instance, to this orbit or some other orbit that we have here. When we bring two hydrogen atoms close to each other, the electron in each hydrogen atom is affected by the field of the adjacent hydrogen atom and, as a consequence, the energy levels are split. Each energy level is split into two energy levels, each slightly displaced from the original energy level. According to the Pauli exclusion principle, you can put two electrons in a given energy state, providing they have opposite spins.

If we look at the bonding of the hydrogen molecule, as the two hydrogen atoms are brought together, there are two electrons to be accommodated; both of the electrons with opposite spins can go into the lower level. With both of the electrons in the lower level, the system has a lower energy; therefore, it takes work to pull them apart when they form a hydrogen molecule because, with the two electrons in the lower level, the system as a whole has less energy. Now, if you consider a helium atom (which has two electrons), as you bring the two helium atoms together, again there are potential fields much the same as in the case of the hydrogen atom. However, now there are four electrons to accommodate, two from each atom; two can go into the upper level and two into the lower level. The increase in energy in putting the two electrons into the upper level is greater than the decrease resulting from the electrons going into the lower level. As a result, the helium does not form a stable molecule because it would require energy to bring the two helium atoms together. Hydrogen forms a stable molecule but helium does not. Ionized helium does form a molecule; that is, if you remove one electron by some external radiation, you have two electrons in the lower level and one in the upper level; the ionized helium molecule has been observed. Now when you bring N atoms together, where N is any number, each one of the levels splits into N levels; so, if six atoms are brought together, each original level splits into six levels. Correspondingly, in a solid which has a large number of atoms, each level splits into N , where N is the number of atoms being brought together. The first slide will illustrate this. (Slide No. 1)

The amount of splitting depends on the distance between atoms. This is the energy between the levels we had previously, and this is the separation. If you start bringing the atoms together, keeping the relative spacing between them the same as you gradually decrease the distance of separation, each energy level splits into six levels. It is possible that all six levels could be filled with electrons, depending, of course, on which atoms are brought together. For instance, the lowest level in the hydrogen atom could accommodate another electron, but in the helium atom the lowest level is completely filled. As electrons are added to the system, they would have to go to still higher unoccupied levels.

slide No. 1 -- Dependence of Energy Levels upon Lattice Constant, or Frequency of Vibration upon Strength of Coupling.

From W. Shockley, "Electrons and Holes in Semiconductors," Copyright 1950, D. Van Nostrand Company, Inc., Princeton, New Jersey

Now, imagine bringing together something like 10^{23} atoms, there would be 10^{23} lines in each energy level, so, for all practical purposes, there would be a continuum of levels. The same condition exists for other energy levels, but between the levels there may be a forbidden energy gap. Just as in the free atom, an electron has to be in one of the allowed energy levels in the solid, so, in principle, in a solid you have energy bands rather than discrete energy levels. The splitting of the levels depends essentially upon the interatomic spacing. It does not depend upon the total number of atoms brought together. There are more states available but, of course, the larger number of atoms you have, the more electrons there are to put into the states; consequently, it all tends to even out. If you have a solid formed from atoms having a high atomic number, the inner core electrons will not split very much because they are still far away from the neighboring atoms in comparison to the valence electrons; normally the splitting is greatest for the exterior electrons.

The energy bands that arise in a solid can be represented by a plot of the total electron energy as a function of distance along the crystal. The ordinate represents the total energy (kinetic plus potential) of the electrons. The splitting of one level made a band such as this but, then again, there might be another level that made this band. Normally, the splitting in the top bands starts to overlap, so there is no concern in showing the top of the band. The region between the bands is a forbidden energy region; in diamond or silicon, all the valence electrons would lie in this particular level. There will be other levels below, which are not broadened; they correspond to energy levels of the inner core electrons. In diamond, silicon, and germanium, the valence electrons occupy all the available energy levels in the valence band. The next higher energy band is unoccupied.

Let us consider the electrical conductivity possibilities of the crystal. In electrical conductivity it is necessary to apply an electric field, which forces the electron to go to higher energy levels because it picks up energy in the field. If a given band is not completely filled, the electrons in the band are free to move to higher levels, with the result that the crystal will conduct a current. If the number of electrons is just sufficient to completely fill the uppermost band, and there is no overlapping of the bands in different directions, we have an insulator. This is true in the case of diamond of high purity and perfect crystal structure. If the band is completely filled when you apply an electric field and if the electrons are to conduct, the electrons have to move to higher energy levels--but there are no allowed energy levels there. It is like trying to apply an electric field to a hydrogen atom; the application of an electric field will not excite the electron into the next energy level. Now, if the energy gap is sufficiently small, at room temperature the electrons can be excited to the next level by thermal excitation; that is, interaction with the lattice can knock an electron up to the next level and if this happens, the electron is free to move when a field is applied. The electron will move into higher energy levels as it moves toward the right in the crystal. This corresponds to so-called intrinsic conductivity. The energy gap in the case of diamond is about 5.6-electron volts; consequently, at room temperatures an insignificant number of electrons can be jostled into the next band, which would be called the conduction band. In the case of silicon, the energy gap is a little larger than one electron volt, so at room temperature a larger number of electrons are able to be thermally excited from this level up to the next level. In the case of germanium, the energy gap is still lower, and in gray tin the energy level is a few hundredths of an electron volt; thus, gray tin behaves almost like a metal in terms of its conductivity. Enough electrons can be excited to the conduction band so that it becomes a conductor. Diamond, silicon, germanium, and gray tin all have the same lattice structure. Once an electron is excited from the filled band to the unfilled band, an energy level is released in the filled band so that another electron can move into the energy level. Therefore, you can achieve conduction in the filled band because carriers in the filled band have freedom of motion.

It is much simpler in the case of the filled band to observe the motion in the energy level that is unoccupied than it is to observe the motion of the total number of remaining electrons. The site where an electron is missing is called a hole. You can talk about conductivity as being due to holes; the holes will move in the direction of the applied electric field, having effectively a positive charge. It is a mathematical convenience to work in terms of the holes.

Now, let us look at some of the features which can readily be explained on a band structure. Photoconductivity is, of course, one of the first things to be noted. If you shine light on the specimen, the light can excite an electron from the filled level to the unfilled level, providing the energy of the photon is equal to or greater than the energy gap in the crystal. Thus, by shining light on a material which is otherwise an insulator, electrons are excited to the conduction band. Therefore, when you apply an electric field, the electrons can be accelerated in the electric field to produce a current. The electrons, of course, when they are excited by light, will recombine in due time with the holes in the filled band.

It is a rather remote occurrence in most materials to have the electrons recombine directly. The majority of materials do not contain the perfect crystal structure that we have shown to give you a perfectly even valence band and a perfect conduction band with no intermediate levels between them. Any crystal, whether it is grown artificially or otherwise, has a certain number of imperfections. The imperfections may be impurities in the crystal or imperfections in the lattice itself, such as dislocations or other lattice imperfections. As a result, whenever you have an imperfection in the crystal, the energy bands are altered near the imperfection. Since the energy level is determined by the field in which the electron moves, if some imperfection is put into the crystal which distorts the field, it is obvious that the energy level is going to be altered also. As a consequence, there are certain intermediate energy states between the filled and unfilled bands. They may be scattered in different spots, but they are localized at some particular position in the lattice. In the case of photoconductivity, for instance, when you shine light having a wavelength short enough to excite an electron into the unfilled band, the electron, generally, would prefer to recombine by some intermediate step such as dropping down to one of the intermediate levels and ultimately back to the filled band. The reason really involves the cross sections of the capturing centers, and the cross sections frequently are much greater for recombination through some intermediate level. Conditions of conservation of momentum and energy are readily met by these intermediate levels.

Now let us examine fluorescence. To be specific, we shall consider diamond which has an energy gap of 5.5-electron volts. It takes a wavelength in the ultraviolet somewhere around 240 millimicrons to excite the electron from the filled band into the conduction band. The electron in the conduction band can now return directly or by way of one of the intermediate energy levels. If it returns by an intermediate level, the energy difference may correspond to visible radiation. Thus, the crystal will show a visible luminescence. The distinction between fluorescence and phosphorescence is determined by the recombination process. If you have an energy level very close to the conduction band, an electron from the conduction band can get trapped in it. At some later time, even after the ultraviolet light is turned off, the trapped electron can be thermally excited into the conduction band and from there return to a lower level with the emission of light. This corresponds to phosphorescence. If the electron drops to a lower level without being temporarily trapped, it is called fluorescence. The distinction between fluorescence and phosphorescence so far as decay time is concerned is not considered a criterion for distinguishing the two. Fluorescence and phosphorescence are distinguished more on an operational basis, depending upon the mode of recombination.

Next, I would like to discuss the origin of some of the intermediate energy levels, specifically considering the cases of silicon and germanium which are semiconductors. To get a semiconductor of the type that is used in transistors, it is

necessary to have an energy level which is very close to the conduction band or an energy level which is very close to the valence band. To do this, you can add an impurity in the crystal which produces an imperfection. In the case of germanium, for instance, if you take a sample of high purity, there would be few energy levels in the forbidden energy gap, but, by adding a Group V impurity such as arsenic, you introduce an energy level for each impurity atom that you add to the crystal. The impurity level will be a few hundredths of an electron volt below the conduction band. The energy gap is around 0.7-electron volt in the case of germanium. Before looking into the origin of the impurity levels, let us indicate what they would mean. In the case of pure germanium the valence band would be completely filled by the four valence electrons of germanium. The impurity level will give an electron state sufficiently close to the conduction band so that the electrons can be thermally excited to the conduction band in great numbers at room temperature, thereby increasing the conductivity. The energy level is called a donor level, and the germanium is called N-type because the conductivity results from negative carriers. Upon addition of a Group III impurity such as boron, energy levels are formed very close to the valence or filled band. They are called acceptor levels because they can accept electrons from the valence band. They are empty at low temperatures, but as you raise the temperature, electrons are excited from the valence band to the empty levels, leaving empty levels or holes in the valence band. As a result, the holes in the valence band are free to move in an applied field. The germanium is called P-type because the conductivity results from the motion of positive carriers.

The next slide will show how you can obtain levels of this type in a germanium lattice. (Slide No. 2) In the case of silicon, each one of the connecting lines represents an electron bond: it is a covalent bond. Each silicon atom has four valence electrons which can be represented by these lines. Each silicon atom is surrounded by four silicon atoms, all at the same distance; therefore, each silicon atom, by sharing electrons with neighboring silicon atoms, forms four covalent bonds. Now, if you add arsenic, which has a valence of 5, there is one extra electron more than required to take care of the four covalent bonds. As a result, in the region around the impurity atom, there is an excess electron. The system looks very much like a hydrogen atom with a single positive charge for the nucleus. The valence of 5 gives one extra charge above the four electrons which shield the nucleus; that is, four of the electrons cancel the effect of four of the positive charges in the nucleus, leaving a net charge of plus 1 in the vicinity of the impurity atom. This looks very much like the hydrogen atom with a positive nucleus and a single negative electron. The electron can move in some energy state or, roughly speaking, in an orbit much like that in hydrogen. This is a crude approximation but it has some substantiation. You can compute the energy required to ionize the hydrogen-type atom just as you would for the hydrogen atom. The ionization energy of hydrogen is 13-1/2 electron volts and, if you divide this by the dielectric constant squared of the material, you obtain the ionization energy of the impurity atom. The electron is in some orbit around the impurity atom, which covers a large number of atoms. The fact that you can use the dielectric constant in this fashion is really justified if the electron moves over a wide region of space, and it turns out that it does; otherwise you would not be justified in using a dielectric constant in this way. An impurity of this type as previously mentioned, gives an energy level a few hundredths of an electron volt below the conduction band. Thermal vibration can tear it loose from the impurity atom and, once it is torn loose, it is free to move through the crystal. If you add a Group III impurity such as boron, which has a valence of 3, you do not have enough electrons to take care of the covalent bonds so you are shy one electron. As a result, an electron moves in from some place farther out in the lattice to take care of the one that is short in this bond. You now have a hole which is moving around the negative impurity center. It is the exact counterpart of the previous case, and you can apply the hydrogen model again. The energy level which is formed is a few hundredths of an electron volt above the valence band. A transition from the valence band to the impurity level corresponds to ionization of the impurity atom. To ionize it means that it takes work to bring an electron from some place out in the perfect lattice and bring it into the hole.

(a) *n*-type silicon

(b) *p*-type silicon

As previously stated, these models are on the rough side. Quantum mechanical calculations have been carried out to obtain the values of the energy levels. If you do the same thing in diamond, for instance, and put in a Group III or V impurity, it should give an energy level which corresponds to approximately 0.35 electron volt. Mr. Stein, who just introduced me, has made optical measurements on some semiconducting diamonds. He observed absorption at 0.35 electron volt. We have some diamonds that have conductivities that are very low. They are highly transparent otherwise, and perfect in other ways, but their resistivities are low compared to a normal diamond. A normal diamond has a resistivity around 10^{14} ohm-centimeters, whereas these specimens have a resistivity of a few hundred ohm-centimeters. Specimens have been obtained with resistivities as low as 25 ohm-centimeters. Upon passing a current through them, the diamonds can be made red hot. We have three of these very rare specimens of diamonds.

The diamond also shows photoconductivity in the visible. Photoconductivity in the visible would imply that there are some energy levels between the conduction and valence bands. We might say one thing about photoconductivity in this connection: all insulators, in general, should be photoconductors. The fact that you can shine light of a wavelength that would excite electrons from the valence to the conduction band, however, does not mean that you are going to observe a photoconductivity as such. The reason is that the electrons may recombine so fast that they are not in the conduction band long enough to detect. The density of the carriers is equal to the rate of generation multiplied by the light times the lifetime of the carrier. This gives the excess number of carriers when light is shined on the specimen. If the lifetime is sufficiently small, the photoconductivity will be there, but it may be a factor of 10^6 smaller than what you can measure because of the lifetime of the carrier. The excess of electrons in the conduction band is a direct parameter involved in the photoconductivity.

The next slide will point out quickly the effect of resistivity changes in a material such as this. (Slide No. 3) In this part of the curve, the resistivity decreases because, in this N-type material, electrons are being excited from donor levels to the conduction band as you increase the temperature. Finally, you come to a temperature at which most of the electrons from the donor levels have been excited to the conduction band. In this region, there is a positive temperature coefficient because all the electrons have been excited to the conduction band; therefore, the resistivity changes because of changes in lattice scattering of the electrons. Then, again, you reach a point where the curve turns over and that is, again, when you have reached a sufficiently high temperature for the electrons to be excited from the valence band into the conduction band. The conductivity increases because of the increased number of electrons in the conduction band. The lattice scattering, of course, still exists, but the increased density of carriers more than offsets it.

Now if we take a crystal of germanium, one side of which is P-type, the other N-type, we will have what is called a P-N junction where the two regions meet. (Slide No. 4)

In equilibrium, the Fermi level must be the same in all parts of the crystal. The Fermi level is the energy level at which the probability of its being occupied by an electron is one-half. The Fermi levels in both sides are equalized by electrons from the N-side diffusing to the P-side and holes from the P-side diffusing to the N-side. As a consequence of the transfer of charge, the resulting electric field alters the energy bands as shown in the next slide. (Slide No. 5) In equilibrium, holes are continually diffusing to the N-side and electrons to the P-side. The holes and the electrons which diffused to the other side may recombine with the carrier of the opposite side or be returned to their original side by the electric field at the junction. Only the electrons and holes which have sufficient energy to overcome the potential barrier can diffuse across the junction.

Resistivity of Silicon-Phosphorous Alloys Versus Temperature

Slide No. 3

From W. Shockley, "Electrons and Holes in Semiconductors," Copyright 1950, D. Van Nostrand Company, Inc., Princeton, New Jersey

(a) DIAGRAM OF SEMICONDUCTOR

(b) DONORS AND ACCEPTORS

(c) CHARGE CARRIERS

(d) NET CHARGE DENSITY,
GIVING A DIPOLE LAYER

(e) ELECTROSTATIC POTENTIAL
CORRESPONDING TO DIPOLE LAYER

DISTANCE THROUGH SEMICONDUCTOR, x

Slide No. 4

From W. Shockley, "Electrons and Holes in Semiconductors," Copyright 1950, D. Van Nostrand Company, Inc., Princeton, New Jersey

Slide No. 5

From W. Shockley, "Electrons and Holes in Semiconductors," Copyright 1950, D. Van Nostrand Company, Inc., Princeton, New Jersey

The junction formed at the barrier acts as a rectifier. Upon the application of a difference in potential across the junction, the height of the barrier is either increased or decreased, depending upon the direction of the applied field. Practically all of the applied potential difference appears at the narrow transition region at the junction because of the high resistivity of the junction. When the P-side is made positive, the barrier height is reduced, with the result that more electrons and holes have sufficient energy to surmount the barrier. This corresponds to the condition for easy flow of current.

The total electron current is composed of electrons crossing from the N-side to the P-side less the electrons crossing from the P-side to the N-side. The latter current is small because the density of electrons in the P-side is small. Similar conditions prevail for the holes.

When the P-side is made negative with respect to the N-side, the height of the barrier is increased; as a consequence, the number of electrons in the N-side which have sufficient energy to cross the barrier into the P-side is reduced and the number of holes which have sufficient energy to diffuse into the N-side is reduced. The return of electrons to the N-side and holes to the P-side is virtually unchanged because they have no barrier to overcome. However, as in the previous case, these currents are small. The net result is that the total current is reduced. In both cases, the change in the height of the barrier is equal to the applied potential difference. The next slide shows the resulting rectification curve. (Slide No. 6)

The following slide shows the behavior of an atomic battery. (Slide No. 7) The atomic battery consists of a P-N junction and a radioactive source such as strontium 90. The emitted electrons from the strontium knock electrons from the valence band in the P-type material into the conduction band with the result that a nonequilibrium density of electrons occurs in the conduction band. The electrons diffuse to the junction and, upon entering the field of the junction, are swept into the N-side. Similar conditions prevail for holes produced in the N-side. The N-side becomes the negative terminal of the battery and the P-side the positive. The difference in the Fermi levels on the two sides determines the emf of the battery. The solar battery is identical in principle with the exception that light is used instead of the radioactive material. The atomic battery may not have too great a future because of radiation damage to the junction.

The next slide shows an NPN junction transistor. (Slide No. 8) It consists of a single crystal, one end of which is N-type, a middle section which is P-type, and the opposite end which is again N-type. Silicon and germanium are the semiconductors commonly used. The middle P-type region is very thin. Electrical connections are made to each of the regions. The next slide shows the resulting energy bands. (Slide No. 9) As you see, there are effectively two P-N junctions. The first junction is called the emitter junction and the next one the collector junction. The emitter junction is biased so that the height of the potential barrier is reduced, and the collector junction is biased to increase the barrier height. With a forward bias on the emitter, the electrons in the N-side can more readily cross into the middle P-region, also called the base. Once in the base region, they diffuse toward the collector junction and, upon getting caught in the strong field of the junction, they are swept into the N-region. If an alternating voltage signal is applied to the emitter junction, the height of the first barrier is modulated with the frequency of the signal, thus periodically allowing more electrons to cross the barrier. The emitter junction, therefore, acts as a control on the current flow in much the same way that the grid does in a triode vacuum tube. Power gain results in much the same way as in a triode. The base layer is kept thin to reduce recombination of electrons with the holes in the base.

Slide No. 6

From W. Shockley, "Electrons and Holes in Semiconductors," Copyright 1950, D. Van Nostrand Company, Inc., Princeton, New Jersey

Courtesy of RCA

Slide No. 7

From J. A. Morton, "Present Status of Transistor Development," Proceedings of the IRE, 40, 1952. (Courtesy of the Institute of Radio Engineers, Inc.)

Slide No. 8

Reprinted with permission from C. Kittel, "Introduction to Solid State Physics," Copyright 1953, John Wiley and Sons, Inc.

Question: Is it possible to make a diamond transistor?

Speaker: This is, of course, an interesting thing to do. We have tried to make a diamond transistor, using semiconducting diamond. We can get transistor action, but thus far we obtain a power loss rather than a gain.

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