CHAPTER IV
PN JUNCTION AND TRANSISTOR PHENOMENA

IV.1 EXORDIUM

Bone, behaving like a semiconductor followed the suggestion of mode of semiconduction in biology (Szent-Gyorgi, 1941). A series of experiments was later performed by Becker et al. in the year 1964 and 1965 in this direction. The semiconduction mechanism may be of a functional significance in biological systems as it has been shown (Huggin and Young, 1957 and 1962) that strong electron donors or acceptors can produce mammary cancer provided the steric configuration of the molecule permitted it to attach to a receptor site in the tissue resulting in charge transfer. The injection of large charge carriers into living systems has been shown to influence growth pattern (Becker et al., 1964). The system operating in the case of bone has revealed that the energy required is due to mechanical forces that are converted into electrical energy. Should the semiconductor properties of bone be changed by stimulations, the structural change in bone is expected. It seems, therefore, that manipulation of control system may eventually result in a clinically useful control of bone growth and architecture.

Starting from the report of existence of piezoelectricity (Yasuda and Fakuda, 1957) down to the studied of Hall effect in bone, every observation was in conformity with the semiconduction
phenomena in other semiconductors. However, the mode of carrier transport in this important material still remains a matter of speculation. A quantitative treatment of PN junction diode characteristics (Becker et al., 1964) did not also fill this lacuna. Hence, the need for such studies was felt. This chapter bears an account of mechanism of conduction in bone and quantification of other parameters.

The semiconduction characteristics of bone are probably related to the semiconduction properties of each of its two major components namely collagen and apatite, which form its basic functional unit (Becker and Brown, 1965) as a PN junction diode (P-apatite, N-collagen).

A comparison between bone diode behaviour and known inorganic semiconductors also seems interesting. This is largely due to the fact that the former can have wide ranging applications. It thus seems imperative that PN junction may be studied in more detail along the established lines. It may be conceded that following points emerge for investigations:

i) PN junction characteristics and their break down region,

ii) Effect of light (Infra red and Ultra violet on the junction,

iii) Use of bone diode as a solar cell,

iv) Photoelectro magnetic (infra red and visible effect of junction, and

v) Examine the bone behaviour in a N-P-N configuration.

In the present investigation an attempt is made to explore these aspects.
Fig. IV.1: Electrode placement for measurements of PNi junction characteristics and photoelectro magnetic studies.
IV.2 MATERIALS AND METHODS

The study was performed on tibia from a freshly sacrificed mature goat. Normal bone samples were obtained and they were supposed to conform to usual structural and mineralization. The bone was treated in a way as described in Chapter II and was given a rectangular shape. The final sample of bone was supposed to consider to be a complex of collagen fibres and apatite crystal having a water content, depending on the room humidity level. In all about thirty samples were tried.

For the study of junction diode characteristics pressure contacts with 26 gauge needle was established (Fig. IV.1). The response failed to show the junction characteristics when the electrodes did not touch the right functional unit, since it was found that placing needle electrodes in a magnetic field caused problems for a strong magnetic field would disturb the needles, therefore, for studying the photoelectro magnetic effect the silver paste contacts were taken and the connections on the sample were made with 40 gauge copper wire. The colloidal silver paint contact observations also showed similar characteristics. The sample was mounted on a holder placed between the pole pieces of an electromagnet such that the light from an infra red radiation source (250 watt phillips lamp) could be focussed on the junction and magnetic field applied parallel to the junction surface.
After the proper PN junction contacts were confirmed (by taking forward and reverse bias characteristics) breakdown region of the diode junction was examined. The diode characteristics were checked after exceeding the breakdown voltage, which was determined by trial. In this way forward and reverse bias characteristics of bone diode were obtained and the observation repeated on the thirty samples of various species (rabbit, rat, goat etc.) under identical conditions.

In case of photoelectro magnetic effect a given value of bias voltage established the current and infra red light was allowed to fall on the junction. A rise in current with time was observed and when it reached to a saturation limit (as confirmed by no increase of current with time for 4-5 minutes), the light was then put off and the fall of current after with time recorded. The observations were repeated after letting the specimens as such for two to three hours. The junction is then exposed to UV light and the sample let at room temperature for couple of hours. The effect of IR light was examined again and the results compared. The experiment was repeated with various values of bias voltage.

In another set of experiments, the junction was exposed to IR/VL (VL = visible light) that results in generation of photocurrent which reached a constant level. At this stage a magnetic field (~16K-Gauss) was put on and off instantaneously.
The resulting increase of current was observed. Magnetic field and the light source (IR/VL) were put off simultaneously and the fall of current with time was noted.

PN junction nature of bone was further exploited to convert solar energy into electricity. The experiments were performed in bright sun shine on bones of different animals. Collidal silver paste contacts were taken on N and P of the bone with 40 gauge copperwise. The sample was placed on a sample holder (Chapter II), under cover. The cover was removed and the junction was exposed to sun light and the rise in voltage was obtained immediately and then its decay was also observed after sun light was obstructed.

After successfully observing the above mentioned PN junction phenomenon in bone, the eye naturally fell on examining and obtaining its electrical characteristics in a N-P-N junction configuration. Figure (IV.2) depicts general circuit (NPN) configuration for studying various types of phenomena such as:

i) Static forward transfer characteristics;
ii) Emitter voltage - Emitter current characteristics;
iii) Collector voltage - Collector current characteristics.

The connections on the sample as usual were taken with pointed silver contacts. A 40 gauge copper wire was used for taking the connections on the sample and connecting wires.
FIG IV 2 NPN CIRCUIT REPRESENTATION IN BONE
In all the cases the connections from the power source and measuring instrument to the sample were taken with shielded wires. The currents and voltages were measured with a 616 Keithley electrometer which was kept in a shielded chamber. The measurements were performed at room temperature and humidity level.

IV.3 RESULTS AND DISCUSSION

IV.3.1 Breakdown phenomenon of PN junction;

When the junction was forward biased i.e. Collagen was connected to the negative of the battery and apatite to the positive of the battery (Fig. IV.1), the current rapidly increased showing a path of lesser resistance. In the case of reverse bias position (Fig. IV.3), the current first increased and latter became constant and in the region of about 2-3 volts and current showed a sharp increase by about one to two orders of magnitude with a little further increase of voltage. The junction is said to be in "Breakdown" region after this point. The current if not allowed to increase to such a value that the junction is destroyed by over heating, the phenomenon is reproducible. The PN junction components were confirmed by the observation that a probable contact to apatite and collagen material surface produced a diode characteristic curve. On the other hand, a probable collagen-collagen and apatite-apatite contact produced a purely linear V-I characteristic. Furthermore, reversal of polarity in
Fig. IV. 3: PN Junction characteristics. The broken line indicates the characteristics below the break down voltage. △△△ represents points pertaining to the observation of Becker.
PN junction contact confirmed the well known reverse bias characteristic. The fact that diode characteristic are obtained only when the contact is across collagen and apatite complex confirms that their formation in full bone has a similar link up as in a well known inorganic PN junction. Failure to obtain such characteristic with Collagen-Collagen or Apatite-Apatite contact substantiates that it is not the in homogeneity at the molecular level. The V-I characteristic are completely reversible in the voltage range under study. On the other hand, in PN junction contact, a breakdown region occurs which makes the V-I characteristic irreversible. Also below a particular value (Breakdown voltage) the V-I diode characteristics are reversible with the experimental error.

The silicon diode which breaks down at voltages below about 5 volts do so mainly under the influence of Zener effect (Becker et al., 1968), however, the breakdown under discussion can not be said as a Zener type for want of other similar data for bone diode. The breakdown may also be of Avalanche Type.

The current-voltage relationship for the PN junction diode is written as,

\[ J = J_0 \left( \exp \frac{\phi V}{kT} - 1 \right) \]  \hspace{1cm} \text{....(IV.1)}

where 
\( J_0 \) = Saturation current 
\( V \) = applied voltage 
\( k \) = Boltzmann's Constant 
\( T \) = Temperature K°
The expression (IV.1) has been arrived by assuming a reasonably band structure model for materials in question. Though no such theoretical data are available or can be easily derived for structures like collagen and apatite yet it is safe to assume that they may have very complex geometry. Hence, in view of this it seems reasonable to assume that the slope (VI) is much steeper than in normal PN junction. This has been attributed to the ratio of drift mobility to Hall mobility - the only probable parameters affecting the carrier transport.

In the spirit of this background \( \phi \) may be then defined as the parameter of the order of the ratio of drift mobility (Behari et al., 1979) to Hall mobility (Behari and Andrabi, 1978) at room temperature \( (T) \) and is taken to be \( 10^{-3} \) in the present case. The plotted curves: (ooo) with the results obtained closely agree with our experimental plot, within the limits of experimental measurements (Fig. IV.3). Also shown in the figure are the results of Becker and Brown (1964), regarding the diode behaviour of PN junction complex. Discrepancy in their data when compared to those of ours may be partly attributed to the possible difference in the physical and thermodynamical state of bone samples in the two cases.

An exact conduction mechanism of PN junction under discussion is difficult owing to the complex structure of bone at the molecular level and hence drawing of energy level
diagrams is not possible in this case. However, a qualitative picture can be presented on the following lines:

The collagen and apatite are cemented together by mucopolysaccharides which is electrically negative (Bassett, 1971). The crystalline collagen tends to have an abundance of electrons; crystals of hydroxy apatite, a lack of them (Bassett, 1965) and as such the interface between collagen and apatite is a semiconductor junction of P-N type. Further, tropocollagen which makes up the native collagen fibril is polar and there is a permanent electric moment in the direction of the longitudinal tropocollagen exis (Athenstaedt, 1970). It has been Figure IV,4) further reported that collagen fibril behaves like an electrical analogue of a permanent rod magnet (Ramachandran, 1967, 1968; Hodge, 1967). Mucopolysaccharides accelerate the process of calcification by regulating Ca^{2+} supplies (Samachsam, 1969) and it take place inside the fibrils of collagen (Glimcher, 1959), therefore, it may be assumed that the calcification generally takes place near the negative and of the native tropocollagen because the inter molecular forces between collagen and inorganic ions must be just strong enough to affect their interaction energies without firmly binding them to collagen structure. For, if either calcium or phosphate ions were very strongly bound by collagen fibrils, collagen would act as a demineralizer similar to cheleting agents, unless a second mechanism were
FIG IV.4 TC Mol

ATTRACTION   REPULSION

P DIPOLAYER M SPACE CHARGE Layer N
APATITE MUCOPOLYSACCHARIDES COLLAGEN

UNBIASED CONDITION

FIG IV.5 Model for PMV junction in the bone.

FIG IV.6 Forward Bias condition.

FIG IV.7 Reverse bias condition.
involved which released the ions after they were bound (Glimcher, 1959). Hence, a layer of mucopolysaccharides along with proteins separates and cements the two main constituents of bone and as such act as both inhibitor and promotor during calcification. We thus arrive at a conclusion which will be determined by the Fig. (IV.5).

Negative charge on tropocollagen molecule are sites for calcification and the introduction of negatively charged mucopolysaccharides molecules is introduced between collagen and apatite during the process. Hence, it may be suggested that the negative charge on M faces the negative charge on N during the formation of bone. The mucopolysaccharides form two different electrically charged layers, namely dipole layer (attraction) on apatite side and unipolar of space charge layer (repulsion) on collagen side. There will be no charge transfer or conduction taking place in the junction say PM or PN because there may be formation of space charge layer in the vicinity of PM junction as the negative charges from 'M' will be attracted towards 'P' which will then produce a negative player on the 'P' side facing 'M' and there is no possibility of conduction between M and N. The extent of this space charge layer between the two materials will be known as "depletion layer".

1. In an unbiased PMN junction there is no applied voltage and junction is in dynamic equilibrium.
ii. In a junction that is forward biased (Fig. IV.6) the positive charge carriers, under the action of applied field cross the potential barrier in P and M side and move towards M and N region and in the process it gets accelerated, thus causing a net current to flow in the PN junction. The path will be of least resistance and therefore the magnitude of current flow is more.

iii. In a junction that is reverse biased (Fig. IV.7), the potential barrier between P and M and M and N increases and the potential barrier widens and the current flow is now less. At a particular critical voltage the molecules get suddenly polarized with the formation of dipoles which are aligned in the direction of the applied field and there is observed an increase in current by about one to two orders of magnitude which can be termed as the "Breakdown" of junction. Beyond this voltage the current remains practically constant. If the voltages applied across this critical voltage then the "Thermal Breakdown" will be achieved which destroys the collagen-apatite fibre (junction) properties and as such as the characteristics are not reproduced.

IV.3.2 Behaviour of PN junction under IR and UV conditions:

The behaviour of PN junction under reverse and forward conditions with different applied biases when subjected to Infra red radiations were studied. It was observed that
current increased and remains constant for a brief time and then starts decreasing (Figs. IV.8-IV.11). A faster decrease is observed when the light is put off at constant current value (mechanism is explained in Part IV.3.3). The observations were again repeated after subjecting bone to ultraviolet light (UVL) for about half an hour. The magnitude of current with IRL was more compared to after UVL, exposures indicating a change in structure at the molecular level introduced by the latter. The PN characteristics of such samples are lost. The observations conclude that the energy of UVL is sufficient to bring the structural changes (by disruption of hydrogen bonds) whereas IRL changes it to significantly lesser extent (Behari and Andrabi, 1978; Behari et al., 1979).

IV.3.3 Photoelectro magnetic (PEM) effect:

PN junction of bone when subjected to infra red light (IRL) and visible light (VL) showed an increase in photocurrent (Fig. IV.12), which are further increased by the application of magnetic field. The phenomenon can be explained as under.

On exposure of junctions (PM, MN) to light they absorb the photons of sufficient energy that results in excitation and migration of charge carriers and some impurities. Consequently number of charge carriers exceeds the value that
Fig. IV.8: Behaviour of PN Junction at 0.2 volts of forward bias under IR and UV exposures. The broken line indicates repeat characteristics after first set of exposures. The dotted line indicates PN junction behaviour during IR exposures after a dose of UV light for a period of thirty minutes.
Fig. IV.9: Behaviour of PN Junction at 0.2 volts reverse bias under IR & UV exposures. The broken line indicates repeat characteristics after first set of exposures. The dotted line indicates PN junction behaviour during IR exposures after a dose of UV light for a period of thirty minutes.
Fig. IV.10: Behaviour of PN Junction at 0.8 volts forward bias under IR and UV exposures. The broken line indicates repeat characteristics after first set of exposures. The dotted line indicates PN junction behaviour during IR exposures after a dose of UV light for a period of thirty minutes.
Fig. IV.11: Behaviour of PN Junction at 0.8 volts reverse bias under IR & UV exposures. The broken line indicates repeat characteristics after first set of exposures. The dotted line indicates PN Junction behaviour during IR exposures after a dose of UV light for a period of thirty minutes.
it is in the absence of radiations and hence an increase of current is observed which shows a steady state after some time. At this steady state value the magnetic field of the order of 16K-gauss was put on and off instantenously and an enhancement in the photocurrent was observed. The phenomenon can be explained by suggesting that the application of magnetic field provies extra energy for the migration of dipoles and hence the enhancement of photocurrent. It was also observed that reversal in the direction of the magnetic field does not change the direction of "enhanced current". It may be suggested that the application of field merely reverses the alignment of charge carriers.

Since the mobility of carriers is much less than unity (Chapter II) and hence the Hoping type (Gutman and Lyons, 1967) conduction model may be operative in such solids.

On further exposure of light after the steady state value the current starts falling. This may be due to the breaking of hydrogen bonds. However, as pointed out earlier (Behari et al., 1979) the energy of these radiations is not sufficient to bring about a completeness of the process. On exposing the sample to UVL for half an hour and repeating the process the photoresponse of PN junction becomes insignificantly less and the effect of magnetic field is also not
Fig. IV.12: Behaviour of Pn junction in a magnetic field. Upper curve shows the rise of current with time during IR light exposures. ↓ ↑ indicating putting off IR light and applying magnetic field. Later portion of curve indicates the fall of current when either of the stimulents have been withdrawn. Lower curve shows the observation as above in the visible light.
clearly preceptible under similar conditions. Thus, it may be suggested that the UVL ruptures the arrangement of the diodes in bone by causing a structural change at the molecular level.

IV.3.4 Bone diode as solar cell:

On entering the PN junction of bone, the photon of appropriate energy excite the charge carriers and a voltage was generated at the P and N side of the junction. In an open circuit the magnitude of the voltage generated varied from 70-100 μV. The resistance between the corresponding junction contact was 20 MΩ. It was thus concluded that PN junction diode behaved as a solar cell and its response to sun light was found to be almost instantaneous. The effect of sun light was found to be reversible if exposed for a short time (10-15 minutes).

IV.3.5 Bone as N-P-N junction transistor:

The various characteristics are shown in figures (IV.13 - IV.15). The following hybrid parameters were also calculated.

\[
\begin{align*}
    h_{11} &= \frac{V_1}{I_1} \bigg|_{V_2 = 0} = 1.5 \times 10^{10} \text{ ohms (input resistance)} \\
    h_{22} &= \frac{I_2}{V_2} \bigg|_{I_1 = 0} = 1.4 \times 10^{-10} \text{ mho (output admittance)} \\
    h_{21} &= \frac{I_2}{I_1} \bigg|_{V_2 = 0} = 7 \times 10^{-2}
\end{align*}
\]
FIG. IV3 STATIC FORWARD TRANSFER CHARACTERISTICS.
FIG IV.14 EMITTER VOLTAGE-EMITTER CURRENT CHARACTERISTICS.
COLLECTOR VOLTAGE (Volts) →

COLLECTOR CURRENT (amps) ↗

\[10^{-11}\]

\[10^{-10}\]

\[\text{ie}= 3 \text{nA}\]
\[\text{ie}= 2.29 \text{nA}\]
\[\text{ie}= 0.65 \text{nA}\]
\[\text{ie}= 0.16 \text{nA}\]

FIG IV 15 COLLECTOR VOLTAGE–COLLECTOR CURRENT CHARACTERISTICS.
where \[ I_1 = \text{Input current} \]
\[ I_2 = \text{Output current} \]
\[ V_1 = \text{Input voltage} \]
\[ V_2 = \text{Output voltage}. \]

It is clear that the device has a high input resistance and low output admittance. It is interesting to compare it with standard (Lowenberg, 1973) NPN transistor (2N117 TypeO) which also has a comparatively high input impedance of 80 ohms and output admittance of \(1.2 \mu \text{mho}\).

In conclusion, the constituents of bone are so fused with one another that they form a junction which are different from those observed in other known semiconduction. Once connections are established they show the characteristics that are identical to those shown by other conventional PN junction diode.

The study further establishes that optical radiations play with the charge carriers and thus alter the electrical behaviour of bone and its constituents. This corroborates some of the earlier conclusions (Behari et al., 1975). The experiments regarding bone solar cell together with other investigators of bone behaviour suggest its potential application in solar energy conversion. The technique being simple and there is no special material supply required. Further experimentation and quantification of various other parameters
may make it possible to fabricate a NPN junction transistor using bone as an essential material for such a device.

In summary, since the electrical activity results in the development of bone and in certain cases carcinogenic type of growth (Huggin and Young, 1962) and magnetic field accelerates the process of bone heating (Becker, 1972) and since mammals are subjected constantly to a particular dose of Infra red radiations this type of study can act as a fore runner for generating some basic data regarding the development of bone under such conditions of environment. The same may be true for other biological materials. Also, this study shows that bone and its constituents can be made both photo and magnetoelectrets and as such they can play a significant role in callus formation (Mascarenhas, 1974).