Potassium Channels: A Transistor Model

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Abstract: Ion involvement of neuronal excitation is well known. Since ions are in the scene, it is possible to visualize the mechanism through the lens of solid state physics. Lipid bilayer acts as a perfect insulator to ions, and transport of the ions - the major current carriers are Na and K ions- across the membrane is observed through ion channels. In this model, axoplasm and extracellular matrix are assumed as p-type material and membrane is as n-type, and for potassium flux whole system is modeled as a pnp type bipolar junction transistor in common base configuration.

Keywords: Axonal membrane, Iontronics, pnp transistors, Potassium flux, Solid state physics.

INTRODUCTION

Besides the many others, the vitality of the living organism highly depends on the fact of nerve excitation. This term mainly refers not only the changes of the different ions across the nerve membrane but also the ion channels that are placed within the axonal membrane. Later issue nerve action potential relatively much more important when compared the former one.

Although the sodium channels are first to be remembered when we discuss the neuronal excitability, still the potassium channels are as much important as the sodium channels. Having responsibilities not only in the repolarization phase of the action potential but also in resting membrane potentials makes potassium channels be an indispensable component of the excitability chain. Besides these important roles for the physiological processes they are the first and the mostly effected channels for the pathological cases which make them an important research focus with different angles of view [1, 2].

Axonal Membrane

It is also well known fact that a membrane through which the solutes and small molecules are passing surrounds the cells membrane. Due to the unique property of the phospholipids, the lipid bilayer membrane acts as a perfect insulator for the charged particles, and the proteins on the other hand embedded in the membrane mediate the ionic transportation [3]. Both sides of the membrane are filled with saline and unlike to the classical current definition in physics – explained by free electron model- currents are generated by the movement of the positive ions across the axonal membrane [4].

Energy Bands and Charge Carriers in Semiconductors

In solid-state physics, the electronic band structure (or simply the band structure) of a solid not only defines the range of energies that an electron within the solid may have (called energy bands, allowed bands, or simply bands) but also dictates the ranges of energy that it may not have (called band gaps or forbidden bands). Theory derives these bands and band gaps by exploratoring the allowed quantum mechanical wave functions for an electron in a large, periodic lattice of atoms or molecules. So the band theory has been successfully used to explain many physical properties of solids, such as electrical resistivity and optical absorption, and forms the foundation of the understanding of all solid-state devices (transistors, solar cells, etc.). Theory very much depends on the Fermi level (total chemical potential for electrons (or electrochemical potential for electrons) and is usually denoted by μ or E_F), the top of the available electron energy levels at any temperatures. The position of the Fermi level with the relation to the conduction band is a crucial factor in determining electrical properties [5, 6]. Schematic representation of conduction and valence bands of a semiconductor is given in Figure **1**.

It is obvious that the electronic characteristics of the solids depend on the band structure of the matter, like insulators semiconductors have a filled valence band, which is distinctly separated from the conduction band via a gap. In comparison to insulators, semiconductors have smaller gaps thus thermal and optical excitation is possible. As the temperature increases thermal excitation of a valence band electron across the gap creates electron-hole pair, the empty state in the

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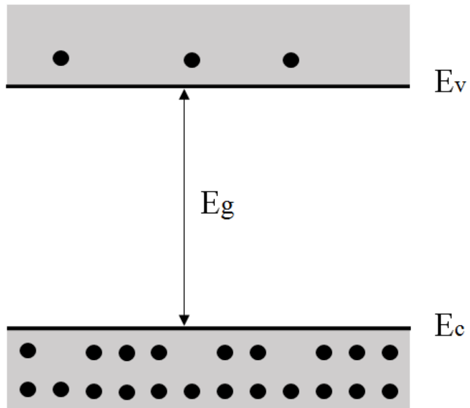

Figure 1: Schematic representation of electron-hole pairs in a semiconductor where E_v is the valence, E_c is the conduction band and E_g is energy gap.

valence band is called as a hole. A hole has a positive charge equal in magnitude to the charge of an electron, and like electrons it can move in the opposite direction to the valence electron through the crystal. Carrier generation and recombination process is fundamental in many semiconductor applications. Direct or indirect recombination occurs when electrons fall from the valence band to the empty states in the conduction band [5, 7].

In a perfect crystal without impurities charge carriers are not present at 0 K. At higher temperatures on the other hand electron-hole pairs are generated by the thermal excitation, since electron and holes are created in pairs the electron concentration in the conduction band is equal to the hole concentration in the valence band. By addition of the doping material it is possible to create n-type (electrons dominant) or p-type (holes dominant) semiconductors. If the doping is done by column 5 elements such as As, Sb, a donor level is created near the conduction band, even at low temperatures the crystal becomes electron dominant, n-type; whereas column 3 elements Ga, In creates an acceptor level near valence band which results in a hole dominant crystal, p type. Application of a negative voltage to the p-region, pulls electrons and holes from the transition region, thus the potential barrier increases, is called as reverse bias. Positive voltage on the other hand decreases the potential barrier and called as forward bias.

Junctions

In semiconductor devices p-n junctions are frequently used for purposes such as amplification, switching and rectification etc. Due to the presence of the majority carrier gradient on both sides, minority carriers diffuse to the transition region. It should be noted that Fermi levels are aligned at the equilibrium, and the difference between the conduction bands is the contact potential. In the forward or the reversed biased cases applied potential is subtracted or added to the contact potential. An I-V characteristic of a p-n junction is given in the Figure **2**. In the positive voltage values drift is dominant, whereas at the negative values only diffusion current is present, diode like character resembles that a favored direction is present at the junction. As seen from the figure, drift current increases exponentially with the applied voltage.

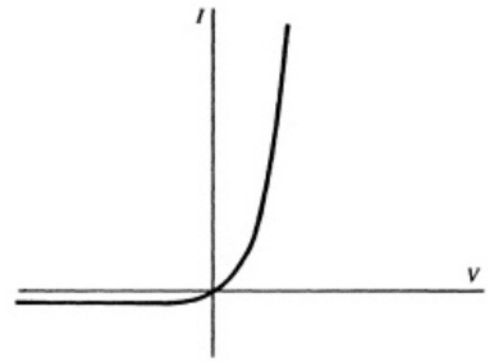

Figure 2: Typical I-V characteristic of a p-n junction.

Fundamentals of Transistor Operations

A transistor -a semiconductor device used to amplify or switch electronic signals and electrical power- is a three terminal device can be found in two types: pnp and npn. In an npn transistor, a thin, lightly doped p-type base is sandwiched between an n-type emitter and an n-type collector; while in a pnp transistor a thin, lightly doped n-type base is sandwiched between a p-type emitter and a p-type collector. Since the majority carrier is positive ions in the axoplasma and extracellular matrix, we will deal with the pnp type. In a transistor, a small change in input current or voltage result in a dramatic change in output. There are two main types of it, bipolar junction transistor (BJT) and field effect transistor. The former uses electron and holes as carrier thus called “bipolar”, and the latter is “unipolar” uses either electron or hole. A BJT is visualized as the connection of two p-n junction back to back one is reversed biased, the other is forward. The contacts are called emitter, base and collector, and usually emitter is heavily doped to increase emission efficiency while the collector is lightly doped. Holes emitted by emitter reach the collector; since the base is n-doped some of the holes are lost through

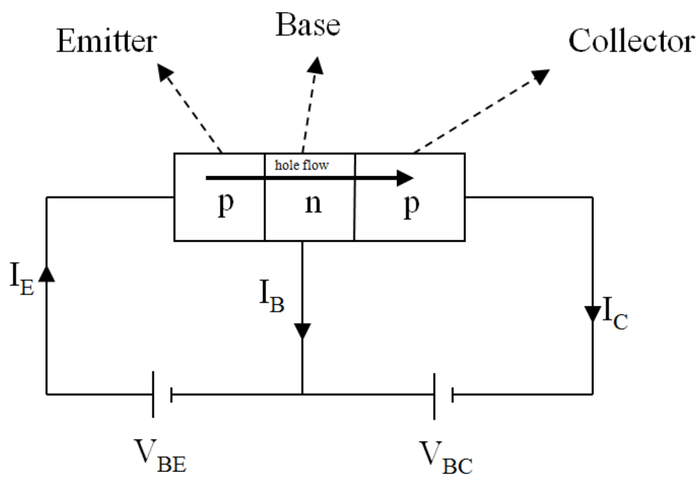

Figure 3: Construction of a pnp BJT with a forward biased V_{EB} and reverse biased V_{BC}.

recombination in the base. Construction of a pnp BJT with a forward biased V_{EB} and a reverse biased V_{BC} is shown in Figure **3**.

There are three circuit configurations of BJTs: common base, common collector, and common emitter. As common base configuration resembles the potassium flux better it is chosen for this model. In this configuration input is the emitter and collector is the output and base is the common terminal. In Figure **4** common base transistor circuit, input and output voltages are shown. It can be characterized with low input impedance, high output impedance, less current gain and high voltage gain. The input characteristic is given in the Figure **5**. It is obtained at constant collector-base voltage by varying emitter-base voltage.

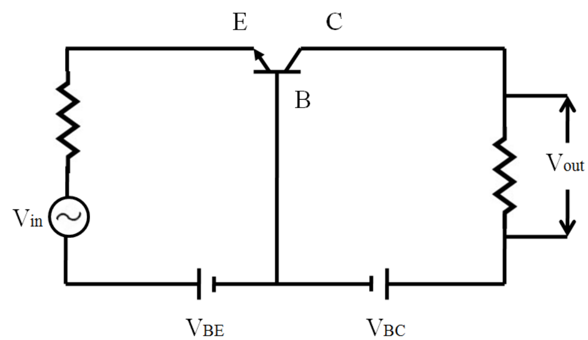

Figure 4: Common base transistor circuit, input and output voltages are given in the figure.

Transistor Analogy of the Axonal Membrane

Learning the intrinsic properties of axonal membrane is important to figure out the excitation

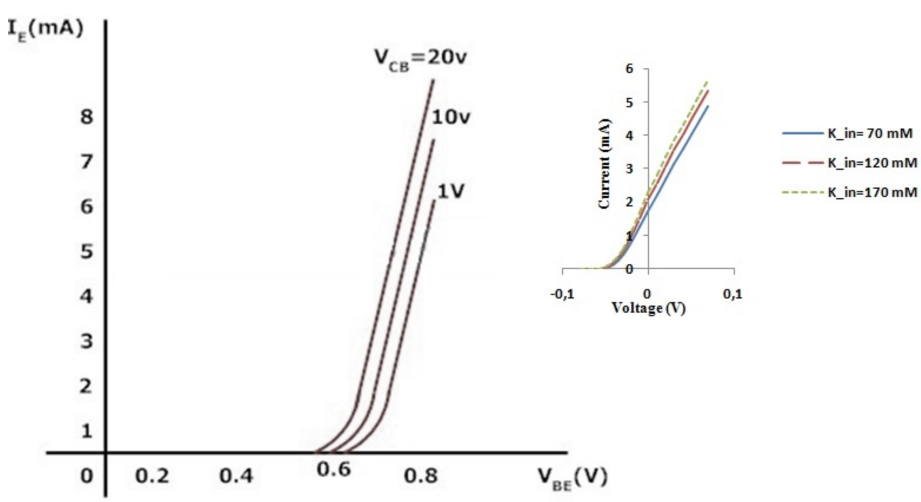

Figure 5: Input characteristic of common base configuration, where input resistance is the slope^{-1}, inset shows the I-V characteristic of the simulated cell membrane, where V_{BE} is the emitter-base voltage and I_E is the emitter current for different base-collector voltages (V_{BC}).

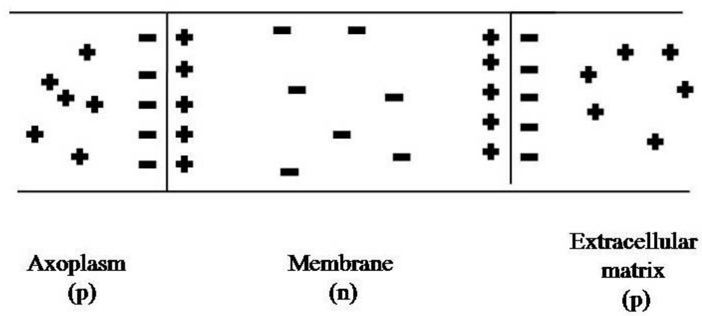

Figure 6: Visualization of axoplasm with respect to solid-state physics. Emitter-base and collector-base voltages can be varied by varying the potassium concentrations.

phenomena for the axonal conduction. Among the many other attempts, optical and electrical models of the axonal membrane would be useful to understand the chain of excitation event. It is important to note that the axonal membrane has the following properties: fixed surface charges, the birefringence changes and the infrared emission [8, 9]. Among these charming properties, surface charge is the most interesting one. It is possible to visualize the phospholipids as dipoles where hydrophobic heads are negatively charged, hydrophobic tails on the other hand are positively charged which is aligned by the membrane. Since the flip-flop movement of the phospholipid is allowed within the membrane, the changes in the dipole may also affect its vicinity. Moreover, surface state plays an important role in the recombination process of the electron-hole pairs. Visualization of axoplasm with respect to solid-state physics is shown in Figure **6**.

Its well known that the main active current carriers are Na^+ and K^+ in the axoplasm and extracellular matrix, so it is wise to assume them as p-type materials, whereas the membrane as n-type. Thus, it is possible to form a transistor analogy of the axonal membrane where axoplasm emits holes and the extracellular matrix collects them and base is the common terminal. The input characteristic of the common base configuration is given in the figure, which very much resembles the potassium flux.

In a cell model changes in V_{BE} can be done by varying intracellular potassium concentration. The simulated potassium currents in different intracellular potassium concentrations are given in the inset in Figure **5**.

Ever since the voltage regulates the opening of the channels, voltage gated ion channels reminds transistor in which current across the transistor is modulated by the applied voltage [10, 11]. The channels, the atomic valves, are atomic size transistor like devices that are more sensitive to the voltage change than transistors [12, 13]. The nature of the voltage channels, may inspire scientists to improve transistor theory, moreover this model may provide two way benefits for the transistor theory and for the ion channels.

CONCLUSION

Since then the time line of Alessandro Volta, ionic contents are used to generate electricity for various purposes. Currently, higher-performance solid-state devices are in nanoscale dimensions, and unfortunately this technology has reached its physical limits because the higher the performance the smaller the dimension. If we need to build higher performance devices it is necessary to find a new perspective. Scientist inspired by nature in many applications due to its efficiency and energy saving characteristics. It is well known that neuronal excitation is mediated by ion transport across the membrane. In other words system generates electrical energy from the present ionic concentration across the membrane, so it is possible to use it in the design of new generation high performance electronic devices. Recently a new technology called iontronics, was developed, which uses ions as active carriers like the one we see in the neuronal conduction. Iontronics uses ionic gradients, unlike the electron-hole pairs it is present, the generation is not necessary, but energy consumption is crucial to keep the ionic gradient at the desired part of the system like Na-K ATPase. Moreover, moving of ions instead of electron and holes is harder and needs more energy. There are several attempts to design electronic devices based on iontronics instead of solid-state electronics though iontronics is far behind it, but the promising results make its candidacy stronger. In an evolutionary manner since the neuronal excitation is evolved is this way, without any doubt iontronics will be used instead of solid-state electronics. This topic needs further investigation.

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