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# Modeling Branched Electrical Circuits with Different Types of Conductivity

**[1] Nikolai A. PARFENTEV and [2] Natalia A. PARFENTYEVA**

[1] All-Russian Research Institute for Optical and Physical Measurements (VNIIOFI), Moscow, Russia
[2] Moscow State University of Civil Engineering (MGSU) National Research University,
Moscow, Russia
Tel.: +7 916 858 8010, + 7 925 0544560
E-mail: nikolaiparfentiev41@gmail.com, nparfentyeva@gmail.com

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**Abstract**: As a model of a developed circuit with different types of conductivity, the principles of operation of bipolar transistors are considered n-p-n and p-n-p. It is shown that an abrupt increase in the input voltage upon the appearance of a collector voltage is associated with disturbances in the energy balance, when the electron energy spent on the metal-emitter barrier transition cannot be compensated for in the base-metal transition. The balance is disturbed due to the different energy spectra of electrons in base and collector.

Fundamental difference in the mechanisms of increasing (in modulus) the base-emitter input voltage with the appearance of a collector potential for transistors of various types are revealed. In is shown that this effect is associated with the sorting of electrons having different average energies in the n-p-n transistor and the mixing of electrons in the emitter of the p-n-p transistor. The concept adopted by us can be useful in the creation of semiconductor devices. It includes not only the properties of semiconductors, but also the properties of metals, with the help of which it is connected to the circuit.

Based on the formulated conditions for electrical circuits with compensated contact potential differences [11], an analysis of the phenomena in a bipolar transistor was carried out.

The contact differences of potentials in a branched chain can be neglected.

1) A relatively small current value at which the Peltier and Zeeman effects can be neglected (intense temperature exchange with the environment).

2) Constant current in all elements of loop current.

3) The conservation of the value of the average energy of charge carriers. As an example, detailed analysis of contact phenomena in a bipolar transistor is carried out. The fundamental difference between the modes of operation of the base-emitter junction in the n-p-n transistor is shown: at zero and non-zero values of the collector voltage.

**Keywords:** Branched chain, Contact phenomena, Bipolar transistor, Semiconductor.

## 1. Introduction

A real electrical circuit usually contains components made from different materials. In classical electrical engineering, this circumstance is usually not given much attention [1-10]. In real conditions, contact potential differences are inevitably present in a closed circuit, but they completely compensate each other, allowing the physical laws, discovered and formulated several centuries ago, to be used quite reasonably for their calculation. On the other hand, the Peltier and Zeeman effects (associated with contact phenomena) successfully work in technology, allowing both to measure the temperature and change its value in the required direction. The physical nature of the contact potential difference provides an opportunity to both increase the energy of carriers falling into the zone of its action, and to lower it. Naturally, specific changes in energy depend on the polarity of the potential difference, the direction of the carrier velocity, and the polarity of the carriers themselves. These phenomena are of particular importance in semiconductor technology, which has penetrated everywhere and has changed practical life, in which they occupy a large and important place. However, contact phenomena are not always correctly explained, since the laws that determine their influence are still not clearly defined.

The purpose of this work is to analyze contact phenomena in classical circuits with different types of conductivity – bipolar transistors of type n-p-n and p-n-p. At the same time, the mechanisms of formation of input characteristics, fundamentally different for transistors of different types, are analyzed. The in-depth understanding, we offer the physical processes in transistors can enter the textbook and reference books on electronics and electrical engineering. It may be necessary and useful material for future engineers and researchers.

## 2. An Example of a Branched Circuit with Contact Potential Differences – Bipolar Transistor n-p-n

A classic example of where the contact difference manifests itself in a paradoxical way is the bipolar transistor, about which everything from school textbooks to serious fundamental books on electronics seems to be written [1]. The first thing we learn from these sources is that a transistor is a device whose main function is to amplify or convert a weak signal from a measuring sensor into a voltage or current supplied to the device.

The most common way to turn on a transistor is with a common emitter circuit for maximum power gain. In this case, both the input current and the input voltage increase at the output of the circuit. For practical calculations, equivalent circuits of real transistors are used, in which there are models of the input base circuit and the output-collector circuit. The main element of this circuit is the current source in the collector circuit, and the magnitude of this current is linearly related to the magnitude of the current in this circuit, and the coefficient determining this relationship is much greater than unity. However, some unexpected phenomenon occurs in the circuit – with the help of the collector current in bipolar transistors of the n-p-n type, it is necessary to increase the voltage supplied to the base. Moreover, this phenomenon, noticeable on real input (basic) characteristics, is of an abrupt nature – it manifests itself immediately after a slight increase in the collector voltage (current). In classical equivalent circuits, this effect is described by the feedback coefficient between the collector voltage and the base voltage.

Fig. 1 shows the equivalent transistor circuitry for small signals. In the input circuit is placed a source of voltage proportional to the voltage of the output circuit.

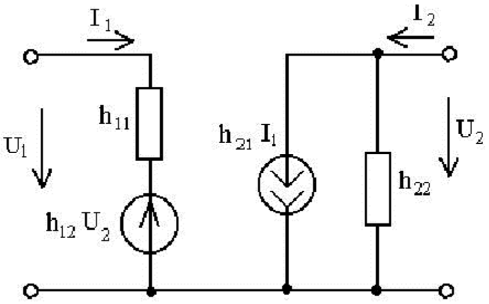

**Fig. 1.** Equivalent transistor circuitry.

The historically equivalent circuitry of a transistor (a linear model of a nonlinear device) emerged at a time when computer simulations had not yet gained momentum. Physical models developed on the basis of solid-state physics were used to describe the operation of a transistor. The band theory contributed to a deep understanding of the processes that determine the mechanisms of the transistor.

However, the linear model of the transistor substitution scheme, created for practical purposes, turned out to be imperfect and did not take into account the peculiarities of the movement of electrons in chains with different types of conductivity.

The interpretation of the increase in the input voltage of transistors as a consequence of the influence of the collector voltage is an obvious logical fallacy. Indeed, both the base and collector voltages are voltages of the same sign. An increase in the base voltage causes an increase in current, the part of the collector voltage appears can only increase the amount of current. In fact, in order to achieve the same current value, it is necessary to increase the supplied base voltage.

The purpose of this article is a physical interpretation of this phenomenon, showing the obvious fallacy of the accepted interpretation. The longevity of this misconception is probably due to the fact that the effect itself manifests itself in the "inoperative" region of the transistor, when the required current gain (the main concern of the transistor designer) is far from the maximum value. LTSpice, an excellent electronic component simulator created to advertise products from the famous Analog Device, fails when trying to describe the operation of a transistor in this area.

Let's analysis of contact phenomena in a bipolar transistor n-p-n.

A fruitful approach to the analysis of a bipolar transistor is the n-p (p-n) junction model in form of a charged capacitor with movable plates, the distance between which can be controlled by changing the voltage applied to the junction. When a reverse voltage is applied, the distance between the plates increases – this is how a varistor works (a capacitor with a variable electric capacitance value). When a direct voltage is applied, the distance between the charged layers decreases so much that a current begins to flow between them and the actually controlled capacitor turn into a controlled resistor (which a variable resistance value).

Unlike a capacitor, where charge carriers are concentrated within the rigid boundaries of metal linings, the charge layers of the semiconductor junction can change their thickness. In particular, the thickness of the charge layer increases with temperature, which explains the dependence of the voltage transition characteristics on temperature.

Now consider in detail what happens in a real transistor switching circuit. In practice, a device whose basic principles of operation are determined by semiconductors is inevitably connected to the measuring circuit using metal contacts. Naturally, in each such connection, a contact potential difference arises. In the diagram shown in Fig. 2, they are represented by voltage sources in the form of circles with a polarity designation – the method adopted in the LTSpice program.

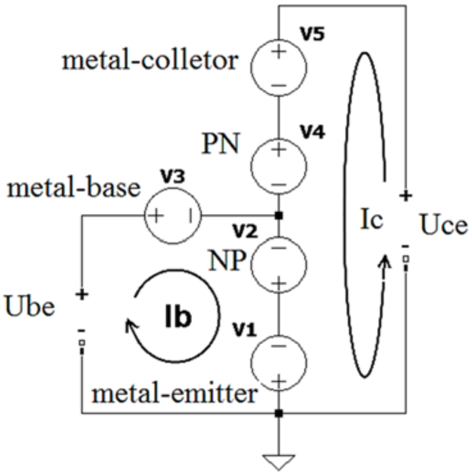

**Fig. 2.** Connection diagram with a common emitter of a n-p-n bipolar transistor. V1 – contact potential difference metal-emitter; V2 – np transition emitter-base; V3 – contact potential difference metal-base; V4 – p-n base-collector junction; V5 – potential difference collector metal.

Blocking and anti-blocking layers may appear at the metal-semiconductor contact. Then such a contact, when an electric current passes through it, will be nonlinear, since its properties change depending on the applied voltage. The existence of a barrier layer at the metal-semiconductor interface and the possibility of controlling its thickness with the help of an external voltage determines the rectifying properties of the contact.

This property, as is well known, is used for point diodes, used, for example, in integrated circuits. The input characteristics of the transistor necessarily include the original curve of the dependence of the current on the input voltage in the absence of the collector voltage, and, consequently, the collector current. At zero collector current, the contact differences of the metal connections of the transistor fully compensate each other, without exerting any influence on the formation of the input voltage, which is completely dependent on the junction voltage np. Naturally, this characteristic is not linear and corresponds to the current voltage characteristic of a semiconductor diode. At first glance, the appearance of the collector current does not change the situation in any way: the contact differences remain the same, and the weak base current, being part of the total emitter current flowing to the base, should not be influenced by the contact differences on the transistor electrodes. In this case, in both cases, the contact potential difference V1, which arises during the metal-semiconductor connection due to the different electron concentration in the metal and semiconductor, is the first barrier for electrons.

As a result, electrons penetrate into the emitter, the average energy of which is less than the average energy of electrons in the metal contact. Let us consider in more detail what happens in the transitions of the bipolar transistor itself in Fig. 3.

Electrons entering the base layer through the emitter move in crossed electric fields. The relatively weak base voltage (Eb) forces them to move along the thin base layer, while the high collector voltage can drag them into the collector junction zone.

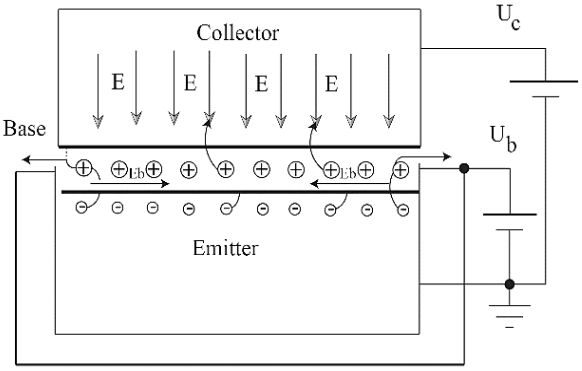

**Fig. 3.** Scheme of a bipolar transistor n-p-n (circuit with a common emitter).

For the most part, electrons with a relatively large kinetic energy get there. Such electrons have a high mobility and are likely are captured by the collector, avoiding the possibility of getting into the base contact. As a result, out of the total number of electrons that passed into the collector through the metal-emitter contact junction, most of them have a higher energy than the electrons entering the base. As a result, the energy spectrum of electrons going to the base differs from the energy spectrum of electrons reaching the collector. The average energy of these electrons is less than the average energy of the electrons entering the emitter. The contact difference V3, which increases their energy, is nevertheless not able to restore its value to the value that they had in the metal in contact with the emitter. Thus, the base-collector branching circuit is a device that sorts electrons by the amount of their energy. The base current does not change, it coincides with the fraction of the current flowing from the metal to the emitter, but the energy spectrum of electrons changes. Thus, when the collector current appears in the base circuit, irreplaceable energy losses occur. The kinetic energy of electrons that have lost energy during the transition of the metal-emitter contact cannot be restored to their original value when passing through the base-metal contact. Thus, an abrupt change in the input voltage with the appearance of even a small collector voltage, or rather the collector current, turns out to be associated with the contact potential difference of the contact base. Based on the above, it is possible to formulate the conditions under which the contact potential differences do not affect the current in the branched circuit:

1) A relatively small current value at which the Peltier and Zeeman effects can be neglected.

2) Equal current value in all circuit elements.

3) The invariability of the mean value of energy spectrum of carriers.

In the base circuit of the transistor, to make up for energy losses when a collector current appears and a concomitant change in the energy spectrum of electrons, it is necessary to increase the input voltage of the transistor.

Fig. 4 shows the dependence of the ratio of the average energy Em of electrons in a metal to the minimum energy of free electrons E0, depending on the value of the minimum energy of the conduction band, expressed in meV, calculated at normal temperature. As follows from the graph, the presence of a contact potential difference that decreases the average energy of electrons is equivalent to an increase in their minimum energy and, consequently, a greater inhomogeneity of the energy spectrum of electrons.

A small increase in temperature will not significantly affect the nature of this dependence, although the conductivity of semiconductors increases.

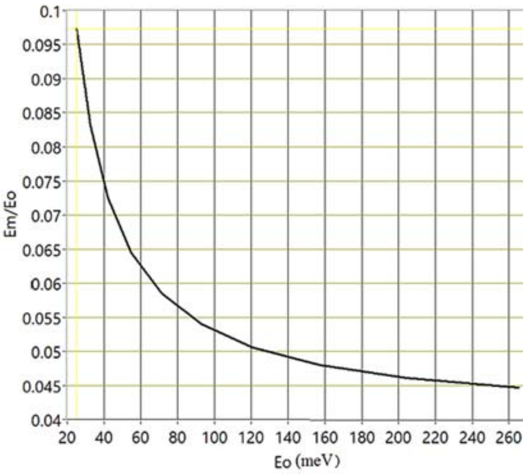

**Fig. 4.** Dependence of the ratio of the average energy of electrons in a metal to the minimum energy on the minimum energy at normal temperature.

A feature of the type of input characteristics of the n-p-n transistor is the high constancy of the amplitude of the input voltage jump. Fig. 5 shows a sample of a typical input characteristic (n-p-n) of an Analog Device MAT-02 transistor.

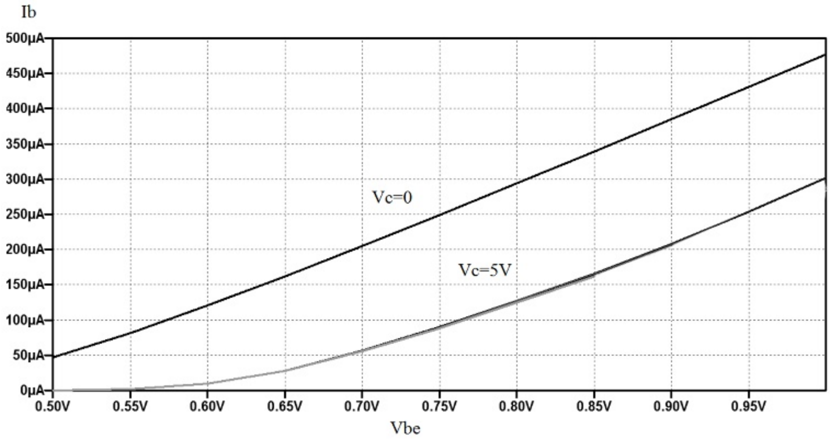

**Fig. 5.** Input characteristics of transistor MAT-02.

It is easy to see that the same value of the input current is achieved by increasing the input voltage by an almost constant increase in the input voltage by an amount equal to 0.2 volts. The constancy of this value is an additional argument in the erroneous interpretation of the input voltage jump from the appearance of the collector voltage. Of course, the accepted interpretation of the effect creates additional difficulties for calculations and design of transistors, since apart from the properties of the transistor itself, the properties of the metal used for contact with the terminals of the transistor must be taken into account. Studying the characteristics of p-n-p transistors, one can notice manifestations of the opposite effect – when the collector current appears, the absolute value of the input voltage decreases. Let's move on to the analysis of the principle of operation of p-n-p transistors, which differ in a different mechanism, causing an increase (in absolute value) of the input voltage when the collector current appears.

## 3. The Mechanism of Formation of Input Characteristics of the p-n-p Transistor

The given characteristics of p-n-p transistors are similar (up to sign) with the characteristics of n-p-n transistors. The input characteristics of this type transistors exhibit the effect of increasing the input voltage (modulo) as collector voltage increases. This phenomenon cannot be interpreted within the collector and base circuit feedback model.

Consider in detail the p-n-p transistor circuit (Fig. 6).

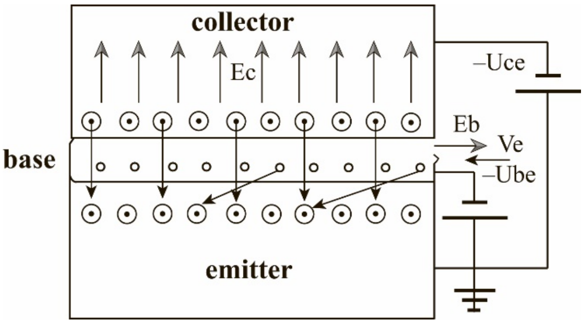

**Fig. 6.** Scheme of a bipolar transistor p-n-p (circuit with a common emitter).

Similar to the n-p-n type transistor, this transistor is a device where crossed electric fields are present. When a sufficient negative voltage is applied, the layers of electrons in the base and holes in the emitter converge so much that the electrons of the base begin to pass into the emitter. Note that the energy of electrons coming from the base has a relatively high value, but in the absence of collector voltage, they come to the plus contact of the base voltage source and all contact potential differences compensate for each other.

When a collector voltage appears, in addition to the base electrons, electrons torn out of the collector begin to flow into the emitter with a relatively small energy characteristic of the process of moving holes in the collector. The energy of the base electrons is higher than the energy of the collector electrons because only the potential difference between the base and the emitter leads to the appearance of current in the transistor, and the voltage on the collector is not enough for it to occur. Then, both streams of electrons are mixed in the emitter and through the common ground wire move to the positive contacts of voltage sources. Due to the significant predominance of the number of electrons from the collector over the number of electrons from the base, the average energy of the electrons is lower than the energy of the electrons of the base.

As a result, the energy balance in the closed base circuit is disturbed and to achieve the same value of the current in the base, it is necessary to increase the voltage of the base source.

The considered mechanisms for increasing the base voltage are radically different in bipolar transistors of different types: in the n-p-n transistor, the cause of the phenomenon is the sorting of electrons of different energies between the base and the collector, in the p-n-p transistor the cause is the mixing of electrons with different average energies coming from the base and collector.

## 4. Analyze a Schema with a Common Base

A common emitter transistor switching circuit was chosen for analysis because the input characteristics of the common-base circuit do not contain a base current measurement.

The input characteristics of a common base transistor n-p-n circuit show a decrease in voltage between the emitter and the base when a collector voltage is applied. At first glance, this circumstance contradicts the provisions of the proposed model.

However, in this case, only the emitter current is measured, which includes the sum of the base and collector currents. With a high current gain, the base current is significantly less than the collector current. Therefore, to obtain the same value of the emitter current, it is sufficient to apply a smaller value of the voltage between the emitter and the base. Naturally, the input characteristics of a p-n-p transistor look similar.

The general emitter circuit provides base current measurements that reflect the physical processes occurring in circuits with different types of conductivity. In the future, we plan to develop a complete model based on experimental data on the study of transistors of different types and inclusion schemes.

This article mainly contains qualitative descriptions of the processes in bipolar transistors. Its results were reported at the MICDAT 2022 conference [11]. In the future, it is planned to develop a model with correct proof of the relationship between changes in the input voltage and contact differences in metal-semiconductor potentials that occur when connecting a transistor.

## 5. Conclusions

1. Conditions have been formulated under which contact potential differences in branched electrical circuits can be neglected.

2. The error of the classical interpretation of the input voltage jump when the collector current appears is shown.

3. A physical interpretation of the effect of a step change in the input voltage of bipolar transistors is carried out.

4. The mechanisms of the input voltage jump are explained: in n-p-n – sorting of electrons, in p-n-p – mixing of electron flows with different average energy.

5. The ways of analyzing the operating mode of bipolar transistors are discussed, which make it possible to eliminate the shortcomings of the existing calculation models.

6. Taking into account the influence of contact phenomena in the transistor connection circuits can lead to an improvement in the operating parameters of the transistors.

7. Ideas about physical processes in transistors, which are included as an important section in textbooks and reference books on electronics and electrical engineering, will serve as a useful material for future engineers and researchers.

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