Experiment No. 20

BOLTZMANN'S CONSTANT FROM V-A CHARACTERISTIC OF PN JUNCTION

OBJECT

1. To determine the Boltzmann's constant from the volt-ampere characteristic of the *pn* junction.
2. To measure reverse current of the *pn* junction for three different temperatures.
3. To plot the volt-ampere characteristic of the junction for previous three temperatures using the dependence of the current on the voltage for *pn* junction.
4. To estimate the error of the Boltzmann's constant.

THEORY

Ohm's law is not a general law of physics; it applies exactly only to electronic conduction in metals. Even for metallic conductors, deviations from the law occur at exceedingly high current densities. Conductors that do not obey Ohm's law are called non-ohmic conductors. Junction semiconductors are the most important of these.

Nonohmic conduction is observed in metallic compounds when the compounds prepared in such a way that they have an excess of one of the constituents - for example, an excess of zinc in zinc sulphide. The nonohmic properties of elements are influenced by doping - the addition of small amounts of impurities selected to be similar, but not quite identical, to the semiconductor molecules in their outer electronic structure. These impurities take up positions in the semiconductor crystal structure in such a way as to produce a local excess or deficiency of electrons.

If there is an *excess* of electrons in the semiconductor structure then such a doped semiconductor is called an *n-type* semiconductor, because the charge carriers are negative. The impurity atoms are called *donors* because they provide the excess electrons.

If, on the other hand, there is a *deficiency* of electrons in the semiconductor structure, called a *„hole“*, then a semiconductor of this types is called a *p-type* semiconductor, regarding the holes as positive charge carriers. The impurities are called *acceptors,* because they can accept electrons into their outer electronic structure. In order to analyze the operation of a non-ohmic device, we must have detailed information about the dependence of the voltage on the terminal of the device on the current through the device. This information is frequently given graphically in the form $I = f(V)$; such a graph is called the volt-ampere characteristic, that is V-A characteristic of the device.

The volt-ampere characteristic of the *pn* junction is described by the following equation

$$I = I_0 \left[\exp\left(\frac{\mathrm{e}\,V}{\eta k T} \right) - 1 \right], \tag{1}$$

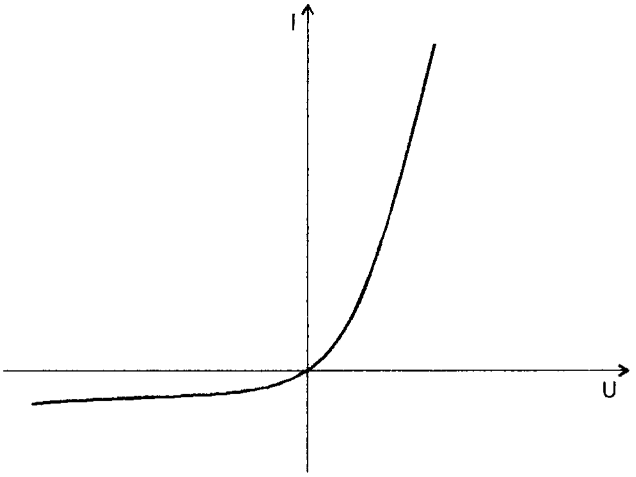
where V is the forward-bias potential difference (taken as negative for a reverse-bias), e is a charge of the electron and η is a correction factor, which depends on the semiconductor material. For our analysis we take η approximately 1, k is Boltzmann's constant and T is a thermodynamic temperature.

For forward-bias potential the current increases exponentially with V. For reverse-bias potential the exponential term rapidly decreases and the current approaches $-I_0$.

Taking into account the fact that I_0 is generally very small the previous expression can be simplified to the form

$$I = I_0 \left[\exp\left(\frac{\mathrm{e}\,V}{\eta k T} \right) \right]. \tag{2}$$

The V-A characteristic of the *pn* junction is shown in the following figure.



V-A characteristic of the *pn* junction.

If the reverse-bias potential is large enough to generate a field of the order of 10 mV/m at the junction, then a charge carrier may be accelerated sufficiently by the field between collisions to break loose another shared electron. This electron is in turn accelerated and may acquire enough energy to disrupt another covalent bond. Thus the number of charge carriers can increase rapidly in an avalanche effect, and the junction diode "breaks down" and becomes conducting.

To determine Boltzmann's constant we shall us Eq. 2 for V-A characteristic of the *pn* junction. If we take the logarithm of this equation we obtain

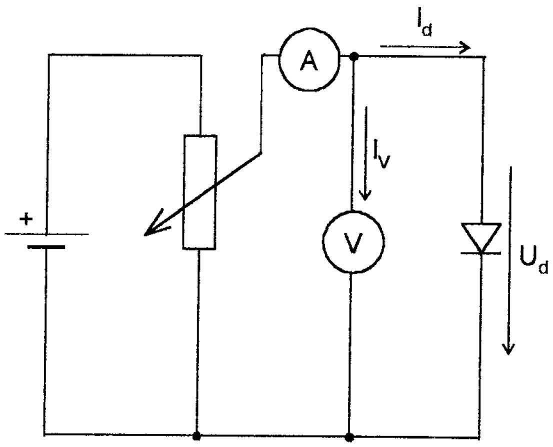
$$\ln I = \ln I_0 + \frac{\mathrm{e}}{kT} V = \ln I_0 + sV .$$

In this equation $\ln I_0$ as well as $s = {}^{\mathrm{e}}\!/_{kT}$ are constants. Therefore if we know the slope s of a line for a particular temperature we can easily determine the Boltzmann's constant as

$$k = \frac{e}{Ts}.$$

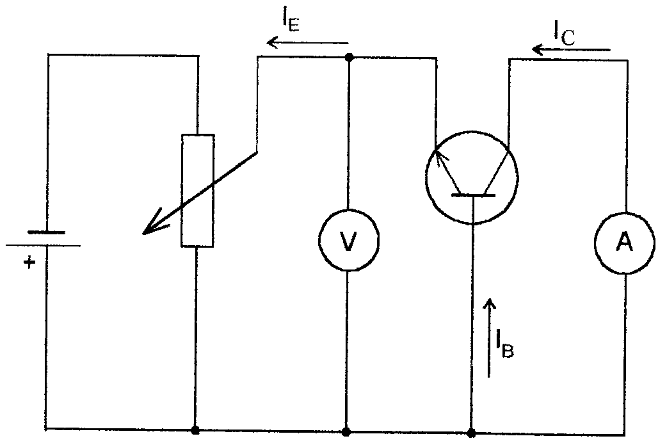
To determine the slope it is therefore necessary to measure V-A characteristic of the junction for a particular temperature. We can proceed in two different ways:

1. It is possible to carry out the measurement using the diode. To decrease the error of measurement it is necessary to use the wiring diagram, which is shown in the following figure. To measure the voltage on the diode it is necessary to use a voltmeter with sufficiently high internal resistance so that for the smallest current of the diode $I_{d,min}$ following condition must be fulfilled $I_{d,min} \gg I_V$, where I_V is the current of the voltmeter.



Circuit diagram to study *pn* junction with a diode.

2. It is possible to carry out the measurement using the transistor with a common basis, see the figure, with a wiring diagram for a transistor. As far as there is a small voltage drop on the ammeter, the voltage between the collector and the basis is approximately zero.

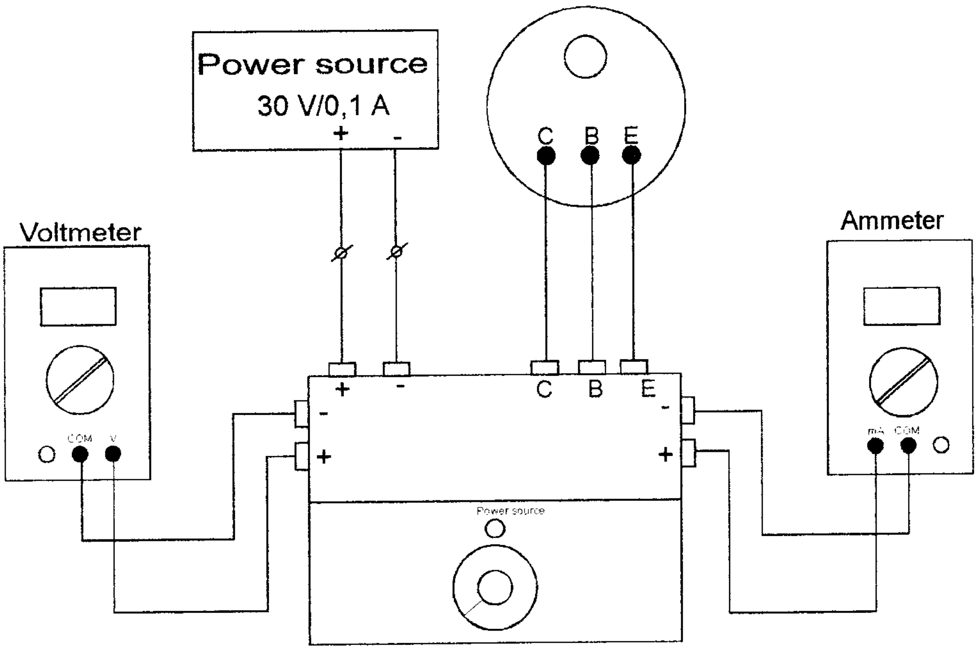


Circuit diagram to study *pn* junction with a transistor.

In this case the reverse current is also almost equal to zero. For the collector current we can write $I_C = \frac{\beta_0}{\beta_0 + 1} I_E$, where β_0 is the coefficient of amplification and I_E is the emitter current. If $\beta_0 \gg 1$ then $I_C \cong I_E$. The emitter current thus passes through the measured *pn* junction base-emitter, from the base continues to the collector where it is measured. Thus the ammeter is not connected series with the junction and therefore it does not influence the junction voltage.

PROCEDURE

1. The experiments should be performed for three different temperatures of the *pn* junction. To do this, place the junction (diode or transistor) into the Dewar flask that is filled with water. For the first measurement choose the water temperature as low as possible. For the second measurement choose the water temperature as high as possible and for the third measurement choose the water temperature in the middle between the previous two temperatures.
2. Connect the *pn* junction into the measurement device following the diagram, which is shown in the following figure.
3. Adjust the voltage of the power supply to 30V and the limit current to 0.2 A.
4. Wait till the temperature between the water and the junction is stabilized. Measure this temperature using the thermometer. Start to measure the V-A characteristic. At the end of the measurement of this characteristic measure the temperature of the water again. For the purposes of calculation determine the average value of the temperature. The measurement of the V-A characteristic is carried out for the forward bias direction only within the range of current from 0.05 till 24 mA.



Top view of the measurement device.

5. At the end of measurement empty the Dewar flask.
6. Analyze the obtained results using the least squares method. From the slope of the line find the Boltzmann's constant and reverse current I_0.
7. Repeat the same measurements for remaining two temperatures.
8. Compare average value of the Boltzmann's constant obtained from these three measurements with the accepted value.
9. Using Eq. 2 and the obtained values of k and I_0 plot the V-A characteristics for all three temperatures.