15. Measurement of the energy gap of the semiconductor.

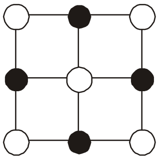
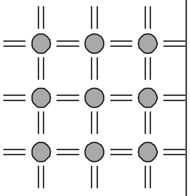
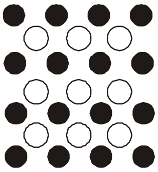
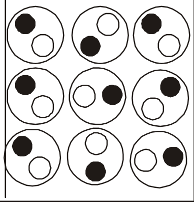
Assignment

1. Measure the V-A characteristic of thermistor at various temperatures.
2. Calculate the energy gap of the thermistor.
3. Discuss the source of errors in the experiment.

Theoretical part

A solid consists of atoms, ions or molecules in close proximity and the forces that hold them together are responsible for the distinctive properties of the various kinds of solids. There are four kinds of bonds of the atoms, ions or molecules to form a crystal *covalent bond* that can link several atoms to form a molecule or solid, *ionic* and *Van der Waals bond* between polar molecules, whose charge distribution is asymmetric, *metallic bond* provide the cohesive forces in solid whose structural elements are ions, molecules and metal atoms. Scheme of physical properties of the crystal types is shown in Tab.9.1.

All these bonds involve electric forces with the difference among them lying in the ways in which the outer electrons shells of the atoms are all altered somewhat by their mutual interactions. In place of each precisely defined characteristic energy level of an individual atom, the entire crystal possesses an energy band composed of myriad separate levels very closed together. Since there are as many of these separate levels as there are atoms in the crystal, the band cannot be distinguished from a continuous spread of permitted energies. The present of energy bands, the gaps that may occur between them, and the extend to which they are filled by electrons not only determine the electrical behavior of solid but also have important bearing on other of its properties. Scheme of physical properties of the crystal types is shown in Tab.9.1.

Crystal	Figure	Interaction	Example	Properties
Ionic		electrostatic $\sim \frac{1}{r^2}$	NaCl binding energy E_b~3.3 eV/atom	hard: soluble in polar liquids (water)
Covalent		shared electrons	diamond, Si, Ge binding energy E_b~7.4 eV/atom	very hard: non soluble, high melting point
Metalic		free electron gas	Na binding energy E_b~1.1 eV/atom	high electrical and thermal conductivity
Molecular		Van der Waals forces $\sim \frac{1}{r^7}$	sugar, ice, Ch4 binding energy E_b~0.1 eV/atom	low melting point and boiling point soluble in covalent liquid

● -electron ◉ -neutral atom ○ -positive ion

Tab.9 1

An interesting property of solid is their electrical conductivity. Some materials are *insulators*, which are extremely poor conductors of electricity (diamond, quartz). Other solid are good *conductors* of electricity (cooper, silver). For example, the electricity of cooper at room temperature is 10^{20} times greater than of the quartz.

Intermediate between these two extreme groups is a third class of solid, called *semiconductors*. Although semiconductors are much poorer electrical conductors than metal, their conductivity increases with the temperature, while the conductivity of conductors decrease with the temperature. Typical semiconductors are germanium and silicon.

The model, which explain the electrical conductivity in solid is called free-electron model. It is based on the principle of quantum physics. When atoms are brought as close together (in crystal), they interact with one another to such an extent that their outer electron shells constitute a single system of electrons common to the entire array of atoms, as is shown in Fig 9.1.

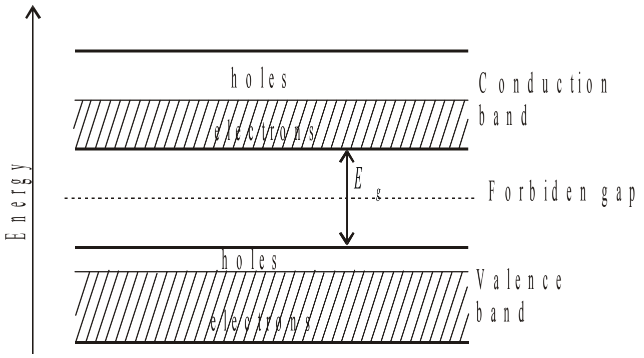


Fig.9.1

The valence and conduction bands in semiconductor are separated by a smaller gap (~ 1 eV) than in the case of insulator (the gap is 6 eV wide in diamond, for example). At the temperature $T = 0$, all states up to certain energy that is called *Fermi energy* E_f, are occupied by electrons. At the temperature higher than $T = 0$, electrons with energies of the top of the valence band can acquire enough thermal energy to jump the gap and enter the conduction band. The Fermi energy is therefore in the middle of the forbidden gap, since the number of electrons in the conduction band equals a number of electrons in valence band. The electrons in the conduction band are sufficient to permit an amount of current to flow if an electric field is applied. For example, in silicon the number of excited electrons is increased by the factor of 10^{16} when the temperature raised from 250 K to 450 K. It is point out that there are both negative and positive charge carries in a semiconductor. When an electron moves from the valence band into conduction band, it leaves behind the hole (vacant crystal state). This hole appears as a positive charge $+e$. The hole acts as a charge carrier in the sence that a valence electron from a nearby bond can transfer into hole. Thus the hole migrates through the semiconductor. In the present of an electric field E, the holes move in the direction of the field and electrons moves opposite the field. Situation is shown in Fig. 9.2. The electrical conductivity in the semiconductors, which we have described is called *intrinsic conductivity*.

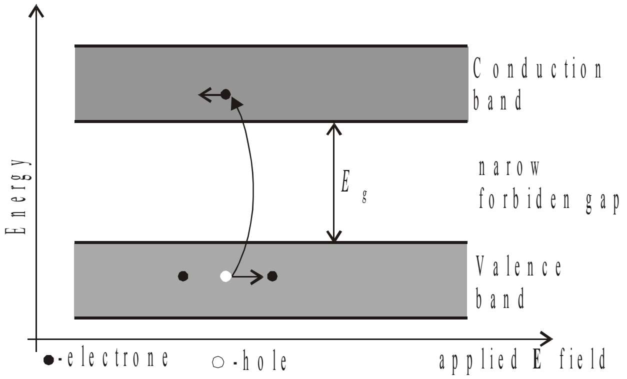


Fig.9.2

From this follows that if the temperature increases, the number of electrons in conductive band in semiconductor increases and we can assume that the resistance of semiconductor decreases as

$$R = R_0 e^{\frac{E_g}{2kT}}, \tag{9.1}$$

where R_0 is the resistance of semiconductor at room temperature T_0, R is the resistance of semiconductor at temperature $T > T_0$, E_g is the width of the forbidden gap and k is the Bolzmann`s constant ($k = 1{,}38 \times 10^{-23}$ J.K^{-1}).

Equation 9.1gives a simple method to measure the width of forbidden gap E_g in semiconductors.

The method-practical part

From the equation (9.1) immediately follows the method of measurement of E_g. Taking the natural logarithm of both sides of eq. 9.1 leads to the following

$$\ln R = \ln R_0 + \frac{E_g}{2kT}. \tag{9.2}$$

From eq. 9.2 we can see that $\ln R$ is linearly dependent on the inverse of the temperature. When we measure the V/A characteristics of semiconductor as function of the temperature, we can determine the width of forbidden band E_g.

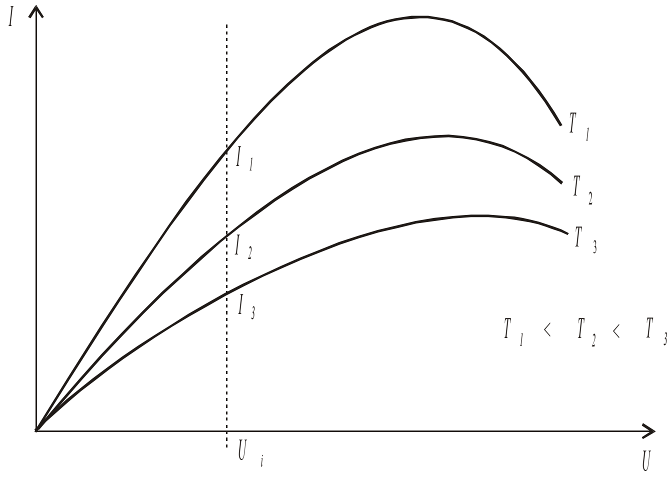


Fig.9.3

Typical V-A characteristics of semiconductor for three different temperatures are shown in Fig 9.3. We shall measure the V-A characteristics of thermistor. Thermistor is the thermometer that has extremely high sensitivity. It consists of a small piece of semiconductor material whose electrical resistance changes with temperature. Thermistors are usually fabricated from oxides of various metal such manganese, iron, cobalt and copper.

Measurement

Apparatus: semiconductor device (thermistor) placed in water, thermostat, reostat, source of voltage, XY recorder.

Experimental procedure: Construct the circuit shown in Fig. 9.4. Heat the water in which is plunged the thermistor. Control the temperature of thermistor with the thermostat. Measure the V-A characteristics of the thermistor for various values of temperature in interval of 0 °C to 50 °C using the X-Y recorder.

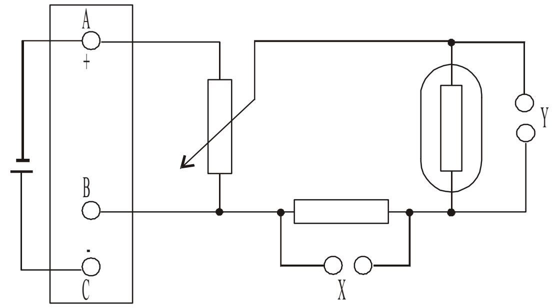


Fig.9.4

Calculation: On the straight line of V-A characteristics determine the points with coordinates U_i, I_i, as is shown in Fig. 9.2. Record these values in the data table Tab.9.1. Calculate the resistance of the thermistor using the Ohm`s law as

$$R_i = \frac{U_i}{I_i}, \tag{9.3}$$

where i is the number of measurement. Record the measured data into Tab.9.2. Determine the slope of $\ln R$ versus $\frac{1}{T}$ by linear regression. From this slope determine the value $\frac{E_g}{2k}$. Discuss the source of errors in your experiment.

Remark: Introduce the value of E_g in eV using the relation $1\,\text{eV} = 1.6\times10^{-19}\ \text{J}$.

i	T_i	$1/T_i$	I_i	U_i	R_i

Tab.9.2