III.5. THE THERMISTOR

1. Work purpose

To check the law describing the temperature dependence of the electrical resistance of semiconductor materials and to evaluate their gap.

2. Theory

Quantum mechanics states that isolated microsystems (electrons, molecules, ions) have only ***discrete energy spectra*** among which transitions are possible. Transitions to higher energy levels require energy absorption from the surrounding media, and those to lower energetic levels occur with energy emission.

As the number of atoms increases, supplementary interactions, which subsequently occur, lead to the splitting of the initial energy levels, the consequence being an enormous number of such levels, grouped in sets, called ***permitted energy bands***. They are separated by domains without energy levels, called ***forbidden energy bands***. The width of a forbidden band is called ***gap***.

Out of these allowed bands, two bands are of particular interest, namely the ***valence band*** and the ***conduction band***. They are separated by a gap $\Delta E \equiv E_g = E_c - E_v$, where E_c and E_v are the bottom of the conduction band and the top of the valence band energies, respectively.

The electrons from the valence band contribute to the atom bonding. These electrons are ***tied up***, meaning they are located in the neighborhood of an atom, not having enough energy to leave it. If they somehow get the necessary energy, they can become free electrons, able to move and,

energetically speaking, belong to the conduction band. As one can see from Figure 1, the energy surplus should exceed E_g.
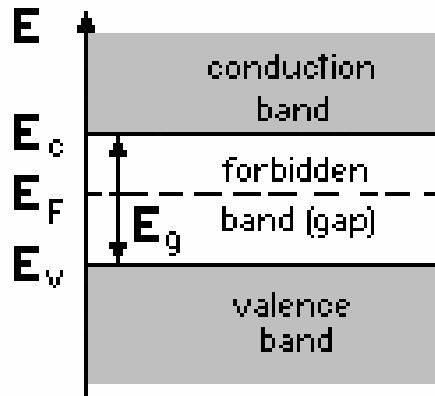

Figure 1.

If the valence (conduction) band is partially filled at absolute zero temperature, all the electrons are nearly free and the substance is a ***metal***.

If E_g is very small, the transfer can easily take place and the substance has a large amount of conduction electrons. This kind of substances is called a ***semimetal***. Both metals and semimetals are ***conductors***.

Conversely, when E_g is very great, the transition is much less probable and the substance is "poor" in conduction electrons. The current is vanishingly small; thus it is an ***electric insulator***.

Between these two extremes are the ***semiconductors***. It is obvious that the gap is of great importance for applications. Actually, the goal of this experiment is evaluating E_g for semiconductors.

For the pure or weakly doped semiconductor materials, at temperatures inferior to some hundreds of Celsius degrees, the Fermi level is situated in the forbidden band, far from both the valence and conduction bands.

For $T \neq 0$, the thermal agitation will generate a concentration of free electrons (quoted n) in the conduction band, while in the valence band will appear holes with a concentration p. If the semiconductor is pure (intrinsic), $p = n = n_i$. The expressions of the two carrier concentrations result from the theory of the energy bands in semiconductor materials:

$$n = 2\left(\frac{m_e^* k_B T}{2\pi\hbar^2}\right)^{3/2} \exp\left(-\frac{E_c - E_F}{k_B T}\right), \tag{1}$$

$$p = 2\left(\frac{m_h^* k_B T}{2\pi\hbar^2}\right)^{3/2} \exp\left(-\frac{E_F - E_v}{k_B T}\right), \tag{2}$$

where m_e^* and m_h^* are the electron and hole effective masses, k_B is the Boltzman constant, T is the semiconductor temperature, $\hbar$ is the Planck constant, and E_F is the Fermi level energy.

Making the product of the expressions (1) and (2) we obtain:

$$n \cdot p = 4\left(\frac{\sqrt{m_e^* m_h^*}\, k_B T}{2\pi\hbar^2}\right)^3 \exp\left(-\frac{E_c - E_v}{k_B T}\right). \tag{3}$$

As $n \cdot p = n_i^2$, one can infer that the carrier concentration in intrinsic semiconductors is:

$$n_i = 2\left(\frac{\sqrt{m_e^* m_h^*}\, k_B T}{2\pi\hbar^2}\right)^{3/2} \exp\left(-\frac{E_g}{2k_B T}\right). \tag{4}$$

The electric conductivity of a semiconductor is:

$$\sigma = \frac{1}{\rho} = e\left(n\mu_n + p\mu_p\right). \tag{5}$$

The mobilities μ_n, μ_p being practically independent of the temperature, it results that:

$$\sigma \propto T^{3/2} \exp\left(-\frac{E_g}{2k_BT}\right), \tag{6}$$

$$\rho \propto T^{-3/2} \exp\left(\frac{E_g}{2k_BT}\right). \tag{7}$$

The semiconductor resistance will then be be:

$$R = CT^{-3/2} \exp\left(\frac{E_g}{2k_BT}\right) \tag{8}$$
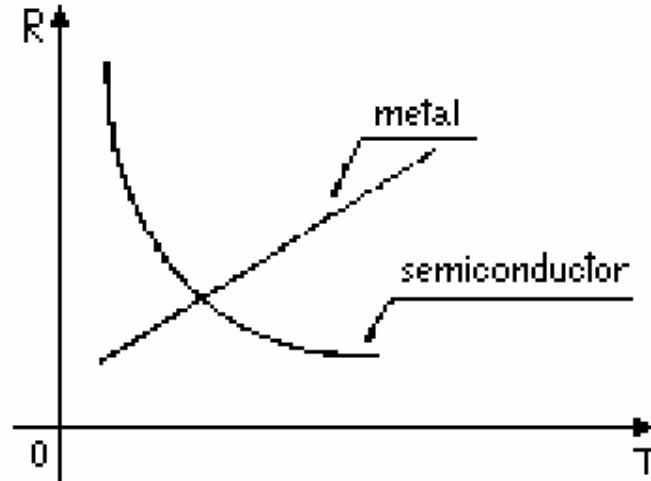
and its temperature dependence is shown in Figure 2.

Figure 2.

Applying the logarithm to Equation (8), one obtains:

$$\log\left(R \cdot T^{3/2}\right) = C' + \frac{E_g}{2k_BT}. \tag{9}$$

3. Experimental set-up

The semiconductor used in the experiment is a transducer called thermistor. Thermistors are semiconductor circuit elements, specially designed and used for the temperature dependence of their resistance. They are manufactured from a mixture of metallic oxides (of Cu, Fe, Cr, etc.), that are ground and pressed together with an organic binder and then

processed. Their shape is usually that of a pill (a), pearl (b), or stick (c). Thermistors are small in size and are characterized by sturdiness, stability of their functional parameters, and low prices. Their main uses in practice are to measure and adjust the temperature in inaccessible places, and to compensate and stabilize the variation of other devices parameters (e. g. the voltage).

Figure 3.

The experimental set up is shown in Figure 4 and it includes an electrical furnace (1) used to heat the thermistor, an ohmmeter (2) used to measure the thermistor resistance, and an electrical transformer (3) used to feed the ohmmeter. The furnace has great thermal inertia, so that although it is not powered through a rheostat but directly from the plug, the temperature increases slowly. Because of this fact the usage of a thermostat is no longer necessary, allowing us to assume that each resistance measurement is performed in quasistatic conditions. The thermometer and the thermistor are attached on the furnace lid .The thermistor has two jacks, which are connected to the ohmmeter by two isolated conductors.

The ohmmeter is built using a Wheatstone bridge. It has a galvanometer (6) as zero instrument, a switch (7) that changes the ranges, indicating the multiplication factor, and a variable resistance (8) with a scale and a runner. A switch (9) in the power source circuit allows the ohmmeter to be fed only during the readings. Some ohmmeters have a built-in button, which replaces the traditional switch. In some other set-ups, the Wheatstone bridge ohmmeters are replaced by simple ohmmeters (ammeters with a reversed scale).
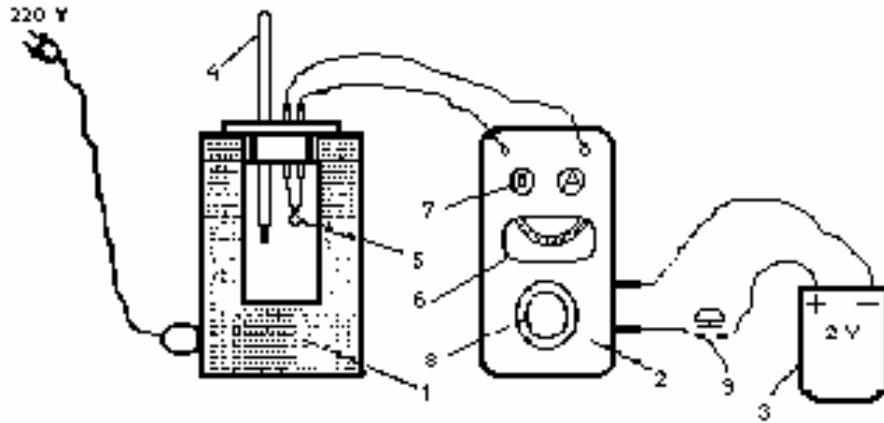
Figure 4.

4. Working procedure

We check the connections from the thermistor to the ohmmeter and the transformer. The first measurement of the thermistor resistance is performed under a professor survey. The runner of the variable resistance is set to the minimum position and the switch of the multiplication factor to maximum. Then the button (switch) must be briefly pressed to observe the direction of the galvanometer hand deviation. Then we must pass to the inferior multiplication factor, quoting again the hand deviation. The operation is repeated until the direction of the hand deviation is changed. Then the button must be pressed permanently, turning the runner, until the galvanometer hand reaches zero. After that the button is released. The thermistor resistance is equal to the value indicated by the runner multiplied by the multiplication factor. At that moment the temperature is also read. If the ohmmeter is of the ammeter type, the readings are made directly. Due to the different heat capacities, the thermometer and thermistor temperatures are not equal. To correct the discrepancy, the measurements are performed during both the heating and the cooling of the thermistor and the mean value of the resistance is evaluated for each temperature.

The results are written in Table 1:

Table 1

t (°C)	R (Ω)			T (K)	$1/T$ (K^{-1})	$\log(RT^{3/2})$
	heating	cooling	mean			
...	...	...	...	...	...	...

The furnace is plugged (or switched on). As the temperature increases, new resistance measurements are performed, without checking again different multiplier factors. The temperature is read immediately after the hand is brought to zero. The temperature interval between two readings is 5 °C and the final temperature must not exceed 100 °C. At the end of the heating the furnace is unplugged (or switched off), and one repeats the measurements during the cooling, at the same temperature values.

5. Experimental data processing

Using the data from the table we draw the $\log(RT^{3/2}) = f(1/T)$ characteristic. Between the experimental points from the characteristic, an interpolation straight line is draw. From Equation (9), the line slope m is

$m = \dfrac{E_g}{2k_BT}$. E_g must be computed in electron volts ($k_B = 8.62 \cdot 10^{-5}$ eV/K).

6. Questions

1. What is a thermistor and why it is more sensitive to the temperature variation than a metal?

2. Which is the filling of the energy levels from the conduction and valence bands for a semiconductor at $T = 0$ K and $T \neq 0$ K?