Determination Of The Energy Gap In Semiconductors

1. The aim of the laboratory

To observe the dependence of the resistance of a semiconductor function of temperature and to determine the energy gap for a given semiconductor.

2. Theoretical approach

Among all materials, the semiconductors, at the room temperature present an electrical conductivity between 10^{-10} – 10^{2} $(\Omega cm)^{-1}$, which is smaller than the metals conductivity and greater than that of dielectrics. Due to this characteristic, the semiconductors are tremendously important in technology. Semiconductor devices, electronic components made of semiconductor materials, are essential in modern electrical devices. Examples range from computers to cellular phones to digital audio players. Silicon is used to create most semiconductors commercially, but dozens of other materials are used as well.

The quantum theory led to the conclusion that electrons in crystals can only have values within permitted bands, separated by energy gaps of forbidden values. The way that electrons can occupy the energetic levels of an allowed band depends on the thermal state of the crystal. At 0 K, the electrons will occupy the permitted levels, starting at lower energy levels, up to a certain band, partially or totally filled with electrons. The highest energy level, which still contains electrons, is called the Fermi level. The energetic bands are conventionally represented like in figure 1 below. The valence band (VB) is the highest energy band, totally or partially occupied with electrons (see Fig. 2). The conduction band (CB) represents the first allowed but completely free band of energy. The band which separates the highest level of VB from the lowest level of CB is called the forbidden band (band gap with energy gap E_g). The width of the gap is determined by the type of the chemical bonds within the crystal and further determines the conduction characteristics of the solid:

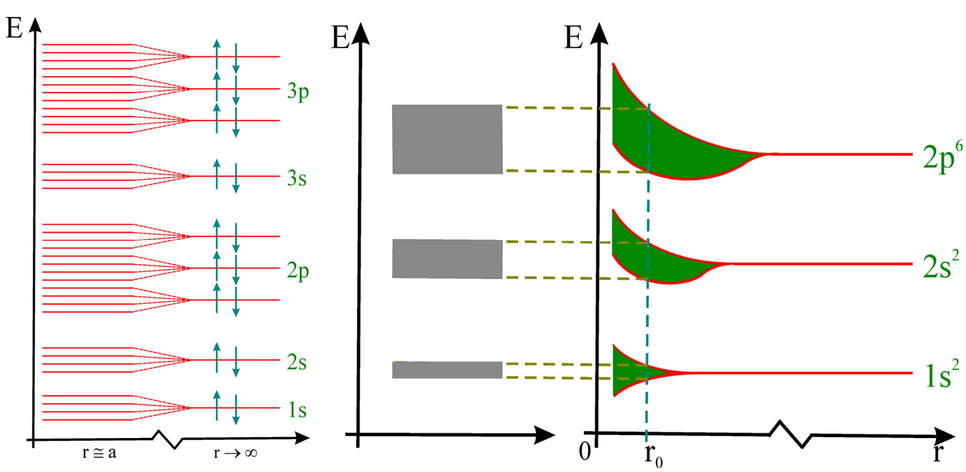

Figure 1.

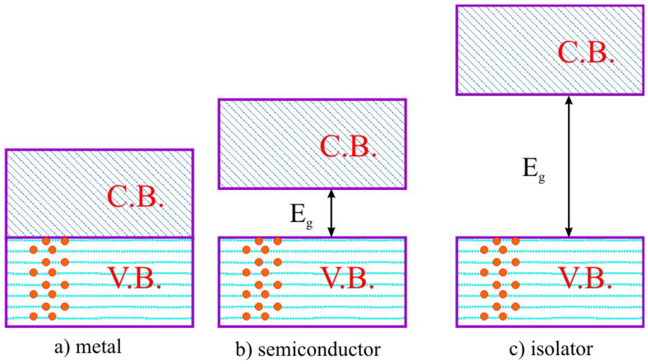

Figure 2.

- $E_g = 0$ if the solid is a conductor (like carbon and metals);
- $E_g < 2$ eV if the substan-ce is a semiconductor and
- $E_g > 2$ eV for an insulator (or dielectric material).

The ionic bond which is formed within dielectrics like NaCl is much stronger than the covalent bond found in pure semiconductor crystals, like Si and Ge. The band gap is larger in dielectrics than in semiconductors. The band gap (E_g) represents the minimum amount of energy necessary for an electron to pass from the VB into the CB: $E_g = E_C - E_V$.

a) Intrinsic semiconductors have no impurities and thus, no additional energy levels in the forbidden band (Fig. 3). When increasing the temperature, the thermal energy of the electrons in VB will increase and the total energy of some e^- attain values within the conduction band. These electrons leave behind, in VB, empty places called *holes*, which are considered to be positive charges, with respect to the negative charge of the electrons. This is the way that the e-hole pairs are thermally generated. If a potential difference is set across the heated semiconductor, this will produce a controlled motion of the charge carriers (electrons travel to the positive pole and holes travel to the negative pole), resulting in a certain electric conductivity of the semiconductor. While increasing the temperature, this conductivity further increases, in contrast with the metals behavior under the same conditions.

b) Extrinsic (or doped) semiconductors have some additional allowed energy levels, between CB and VB. These additional energy levels are due to the impurities or to the lattice defects, present in the semiconductor crystal (see Fig. 4). The conductivity of semicon-ductors is characte-ristically a function of the temperature. Three ranges are distinguished (see Fig. 5): i) at low temperatures we have extrinsic conduction (range I), i.e. as the tempera-

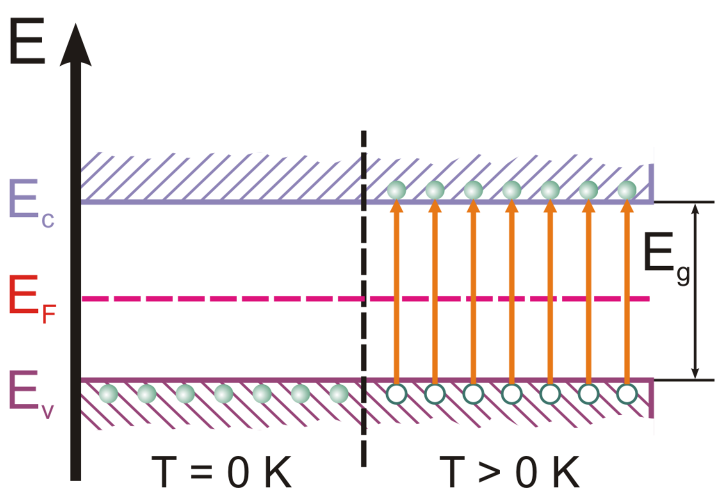

Figure 3.

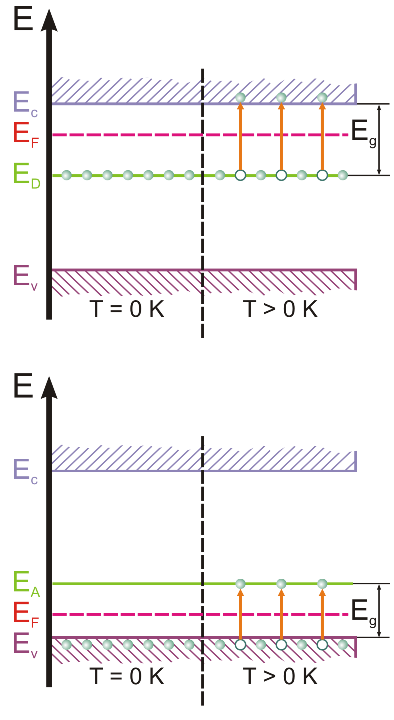

Figure 4.

ture rises, charge carriers are activated from the impurities; ii) at moderate temperatures (range II) we talk of impurity depletion, since a further temperature rise no longer produces activation of impurities, and iii) at high temperatures (range III) it is intrinsic conduction which finally predominates: charge carriers are additionally transferred by thermal excitation from VB to CB. Temperature dependence is now essentially described by an exponential function:

$$\sigma = \sigma_0 \cdot e^{\frac{E}{2kT}}, \qquad (1)$$

where E_g is the energy gap, k is the Boltzmann's constant and T is the absolute temperature. The logarithm of this equation:

$$\ln\sigma = \ln\sigma_0 - \frac{E_g}{2kT}, \qquad (2)$$

is with $y = \ln\sigma$ and $x = 10^3/T$. A linear equation of the type $y = a + b \cdot x$ where $b = -E_g/2kT$ is the slope of the straight line.

For the extrinsic semiconductors, the forbidden band is much decreased in the presence of either the acceptor (EA) or the donor (ED) levels respectively. Therefore, a smaller gain in the energy of the electrons will create charge carriers: e^- in CB for crystals doped with donors and h^+ (holes) in the crystal doped with acceptor impurities. Since the conductivity of metals follows an exponential law, as written above, it follows that the resistivity of semiconductors decreases with increasing temperatures, obeying the law:

$$\rho = \rho_0 \cdot e^{\frac{E_g}{2kT}}, \qquad (3)$$

where ρ is the resistivity of the semiconductor at T (K), ρ_0 the semiconductor resistivity at T_o (K) and E_g is the energy gap.

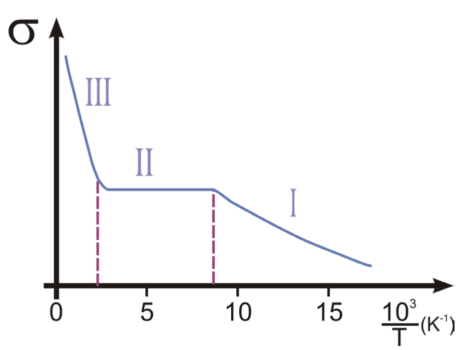

Figure 5.

The resistance of the semiconductor, given by:

$$R = \rho \cdot \frac{l}{S}, \qquad (4)$$

also decreases while increasing the temperature:

$$R = R_0 \cdot e^{\frac{E_g}{2kT}}, \tag{5}$$

and by applying *ln* to this equation, one obtains:

$$\ln R = \ln R_0 + \frac{E_g}{2kT}. \tag{6}$$

If the decimal logarithm is further considered, the above relationship becomes:

$$\begin{gathered} \ln R = \ln R_0 + 0.43 \cdot \frac{E_g}{2kT} \quad or \\ \ln R = a + b \cdot \frac{10^3}{T} \end{gathered} \quad . \tag{7}$$

Therefore, a graph showing the dependence of *lg*(*R*) on $10^3/T$ is represented by a straight line (Fig. 6) whose slope helps finding the band gap E_g:

$$\begin{gathered} \tan(\alpha) = 0.43 \cdot \frac{E_g}{2kT} \quad \Rightarrow \quad E_g = \frac{2k}{0.43} \cdot \tan(\alpha) \quad (J) \quad or \\ E_g = 0.2 \cdot \frac{\lg R_2 - \lg R_1}{\frac{10^3}{T_2} - \frac{10^3}{T_1}} \quad (eV) \end{gathered} \quad . \tag{8}$$

3. Applications

Due to the large sensitivity with temperature of electric conductivity, the semiconductors can be thermally activated and can serve as central element in the construction of simplest device with high accuracy at the measurement of temperature variation. The *thermistor* is a semiconductor of which thermal resistance depends in controlled mode of temperature. The thermistors are constructed by mixing of some metallic oxides using special technologies and are characterized by a series of parameters like: (i) nominal resistance at 20 ºC, R_{20}, (ii) the gap of forbidden band for the intrinsic semiconductor, $B = E_g/2K$, named also material electronic constant, (iii) the thermal coefficient, $\alpha_T = -B/T^2$, (iv) the maximum admitted temperature T_{max}, which is the threshold temperature, as well as (v) the domain of temperature variation (-150ºC÷2000 ºC). The thermistors have various applications in the measurement, adjustments and control of temperatures from diverse parts of industrial processes.

The varistors are nonlinear resistances made from silicone carbide. These are used in high voltage lines. More varistors connected in series can constitude a discharger, where one therminal is connected to high voltage line and the second thermial is grounded. If the line is striked by a thunderbolt, due to the extremly high voltage the resistance of the discharger decay dramatically then through this device an important amount of current goes to eart protecting in this way the high voltage line.

The semiconductive materials are at the base of all electronic components and integrated circuits. The apparition of nanomaterials leads to the miniaturisation of semiconductors and of all electronic components. Therefore, all semiconductors thermally activated or subjected to diverse types of radiations can be integrated in all new miniaturized devices including nanorobots.

4. Experimental set up and procedure

The resistance of semiconductor test-piece is to be measured as a function of temperature. The ln(R) is to be plotted against the reciprocal of the temperature. A linear plot will be obtained from whose slope the energy gap of the semiconductor can be determined.

The experimental set-up is as in figure 6. The test piece is connected to an ohmmeter and is electrically heated. The heating coil is supplied by an alternating voltage output of an autotransformer. The test-piece is to be warmed up slowly. The maximum permissible temperature of 110 ^{o}C must not be exceeded.

The test-piece temperature is determined using a cromel/Cu thermocouple and a mV-meter (calibrated in ^{o}C). An ohmmeter - indicates the values of the resistance at different values of t(^{o}C). In figure 6 we have the components: electrical oven, semiconductor test-piece, thermocouple, milivoltmeter (directly indicates the temperatures). We know: 1e = $1,6.10^{-19}$ C, and 1eV= $1,6.10^{-19}$ J.

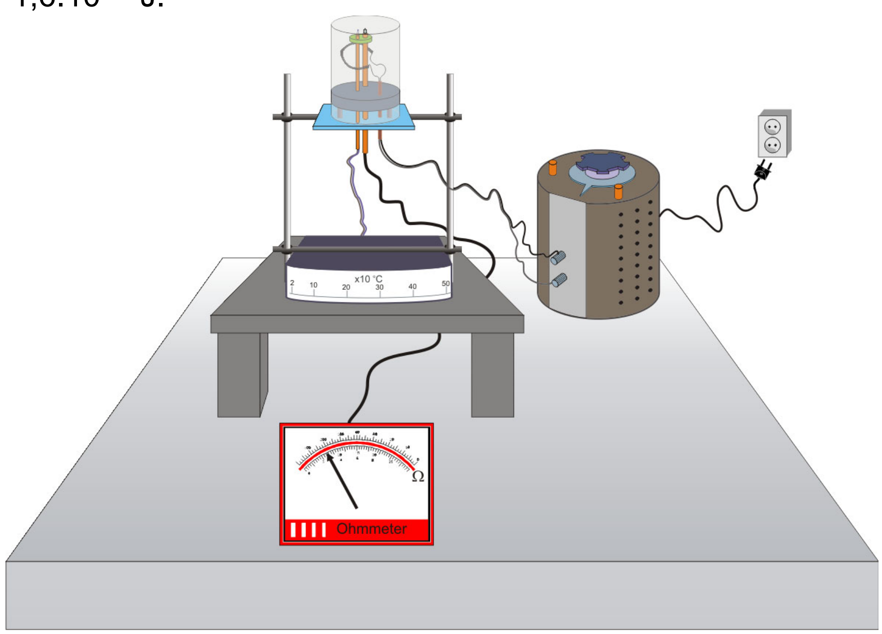

Figure 6.

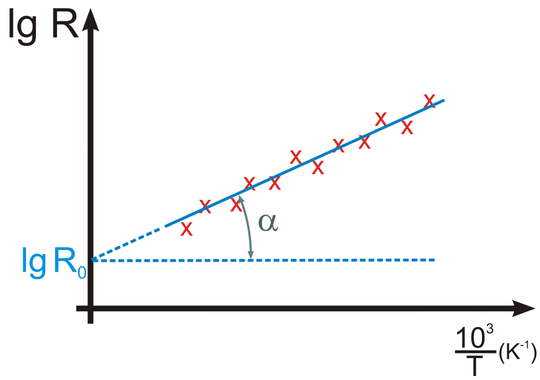

Figure 6.

5. Procedure

1. One measures the resistance of the semiconductor at the room temperature.

2. One plugs the oven and reads the resistance of the semiconductor at each 10 ^{o}C increase of the temperature of the oven. All data are to be recorded in the Data table. The temperature must not exceed 100^{0}C !!

3. One plots the dependence of lgR on $10^3/T$, as in figure 6.

4. One calculates the slope of the line and further estimates the band gap of the test-piece semiconductor, by using the formulae deduced in the previous section.

5. Computing the relative deviation:

$$\frac{\Delta E_g}{E_g} = 2 \cdot \frac{\Delta T}{T_2 - T_1} + \Delta T \cdot \left(\frac{1}{T_1} + \frac{1}{T_2} \right) + \Delta R \cdot \left(\frac{1}{R_1} + \frac{1}{R_2} \right) \cdot \frac{1}{\lg R_2 - \lg R_1}, \qquad (9)$$

which was deduced, considering that: $\Delta R_1 = \Delta R_2 = \Delta R$ and $\Delta T_1 = \Delta T_2 = \Delta T = 10^0 C$.

Tabel 1

t [^{o}C]	T [K]	$\frac{10^3}{T}$ [K^{-1}]	R [kΩ]	lg R -	ΔE [eV]	$\frac{\Delta(\Delta E)}{\Delta E}$ [%]
20						
30						
40						
50						
60						
70						
80						
90						
100						