Z9 – Physical properties of semiconductor devices

Physics Laboratory II – academic year 2017/2018
Faculty of Physics, Astronomy and Applied Computer Science, Jagiellonian University

The aim of this laboratory class is to introduce students to the physics of semiconductor devices. It is realized by:

- determination of impurity concentrations in tunnel diode,
- determination of the e/k ratio from the $I_C(U_{BE})$ current-voltage characteristic of bipolar transistor,
- measurement of the current-voltage characteristics of typical rectifier diodes (silicon and germanium ones) and comparison with the $I_C(U_{BE})$ characteristic of bipolar transistor,
- observation of the Zener effect or avalanche breakdown on the basis of current-voltage characteristics of typical Zener diodes,
- determination of the hc product from the current-voltage characteristics and emission spectra of light-emitting diodes (LEDs).

Attention! The laboratory class covers a wide range of knowledge and can last from one week up to four weeks depending on the program. That is why student is obliged to contact the assistant responsible for the class in order to set down the program and required range of knowledge. In case of no contact, all topics mentioned in the *Preparatory questions* section are obligatory.

Preparatory questions

The required range of knowledge depends on the programe.

Common questions:

1. Conductors, semiconductors and insulators – electrical properties, theory of electrical conductivity and resistivity [1].
2. Band theory of solids [1].
3. p-n junction (diode) – theory of operation, current-voltage characteristic [1].

Detailed questions:

1. Determination of impurity concentrations in tunnel diode:
   - tunnel diode – theory of operation, current-voltage characteristic [1, 2]
   - degenerate semiconductor [2]
2. Determination of the e/k ratio from the $I_C(U_{BE})$ current-voltage characteristic of bipolar transistor:
   - bipolar transistor – theory of operation, characteristics [1, 3]
3. Measurement of the current-voltage characteristics of typical rectifier diodes (silicon and germanium ones) and comparison with the $I_C(U_{BE})$ characteristic of bipolar transistor:
   - bipolar transistor – theory of operation, characteristics [1, 3]
4. Observation of the Zener effect or avalanche breakdown on the basis of current-voltage characteristics of typical Zener diodes:
   - Zener diode – theory of operation, current-voltage characteristic, Zener voltage [1, 4]
5. Determination of the hc product from the current-voltage characteristics and emission spectra of light-emitting diodes (LEDs):
   - LED – theory of operation [5]
   - optical grating spectrometer – theory of operation (knowledge taken from any handbook on experimental physics)

Computational assignments

1. Carrier concentration in intrinsic semiconductor depends strongly on temperature and is proportional to $\exp(-\frac{E_g}{2k_B T})$ where E_g denotes energy gap, k_B – the Boltzmann constant and T – temperature. Calculte relative change in the carrier concentration related to the temperature rise from 300 K to 330 K. Assume E_g equal to 1.11 eV and 0.66 eV for silicon and germanium, respectively.
2. LEDs (red, green and blue) show maximum intensity of emitted light for the wavelengths of 630, 520 and 470 nm, respectively. Calculate corresponding energy gaps. Express the result in eV.

Apparatus and materials

The experimental apparatus is presented in figure 1 and it includes the following equipment and elements:

- power supplies with controlled output voltage
- digital multimeters
- heater with temperature controller

Figure 1: Experimental apparatus.

- digital thermometer
- investigated devices: diodes, n-p-n bipolar transistor
- optical grating spectrometer
- wires

Experiment

1. Build an electric circuit following selected diagram.
2. Using multimeters collect necessary chracteristics.
3. While investigating LEDs record their spectra with the use of optical grating spectrometer.

The circuit diagrams and hints concerning measurements are available in appendices A-E.

Data analysis

Depending on laboratory class program, calculate such quantities like: impurity concentrations in tunnel diode, e/k ratio or hc product. While investigating bipolar transistor and/or rectifier diodes determine the m empirical parameter as defined in the paper by Inman & Miller [3]. Compare the values of m found for the diodes with that found for bipolar transistor. In all cases uncertainties of above mentioned quantities also have to be estimated. The obtained results have to be compared with accepted values if available.

The details concerning data analysis can be found in appendices A-E.

Safety rules

- The voltages and currents appearing in the investigated circuits are not dangerous for human beings, nevertheless, one should take into account that devices such as power supplies and digital multmeters are powered by the mains voltage of 230 V, so standard safety rules concerning working with electrical equipment are mandatory.
- Collecting characteristics of bipolar transistor takes place at temperatures reaching 80^{o}C, so avoid direct contact with transistor heat sink. From time to time ensure that heat sink does not touch any flammable or temperature non-resistant objects like for example wire insulation.

References

[1] R. Eisberg, R. Resnick, *Quantum physics*, John Wiley & Sons, New York, 1985, chap. 13.

[2] B. G. Streetman, S. K. Banerjee, *Solid State Electronic Devices*, Pearson Education Inc., 2005., chap. 10.1.

[3] F. W. Inman, C. E. Miller, "The Measurement of e/k in the Introductory Physics Laboratory", *American Journal of Physics*, Volume 41, Issue 3, pp. 349-351 (1973).

[4] B. G. Streetman, S. K. Banerjee, *Solid State Electronic Devices*, Pearson Education Inc., 2005., chap. 5.4 (In the text abbreviation EHP stands for an electron-hole pair).

[5] *Introduction to Light Emitting Diodes* http://micro.magnet.fsu.edu/primer/lightandcolor/ledsintro.html

Appendix A

Determination of impurity concentrations in tunnel diode (Details of experiment and data analysis)

Experiment

1. Build electric circuit according to fig. 2. Do not switch on power supply.

2. Balance the bridge.

   The circuit is based on idea of the Wheatstone bridge, so balancing the bridge is necessary to obtain reliable results. **Make sure that the SW1 switch is in the *off* position** (the diode is disconnected). Set the output voltage of power supply to zero and switch it on. Increase gradually supply voltage until the V1 voltage reaches 0.5 V and observe the voltage reported by the V2 voltmeter. The V2 voltage should be supply voltage independent and close to zero within whole supply voltage range. If it is not the case, correct it using a screwdriver for setting the potentiometer. Remember that after each supply voltage change the circuit needs a while to reach thermal stability.

3. Set supply voltage to zero and then switch on the SW1 switch (the diode is connected). At that point it is **highly recommended to set the current limit of the power supply** in order not to destroy the tunnel diode. Increase gradually supply voltage and observe I(U) characteristic of the diode (the voltage on the diode is reported by the V1 voltmeter while the diode current is proportional to the V2 voltage). A *peak* and a *valley* should be noticeable. In case of the investigated circuit a "false valley" often appears due to the fact that in the region of the I(U) characteristic with negative differential resistance the circuit easily becomes a high-frequency oscillator. This effect interfers with detection of a true static I(U) characteristic. The "true" valley is located at slightly higher voltage than the "false" one.

   Detect the ("true") valley voltage and set the power supply current limit to such a value that the diode current above the valley does not exceeds 120 % of the valley current.

4. Collect the I(U) characteristic of the tunnel diode with increasing voltage. Increase the number of experimental points in the neighborhood of the *peak* and *valley* voltages. Optionally a characteristic with decreasing voltage can also be taken.

Data analysis

1. Draw the I(U) characteristic of the investigated tunnel diode. Determine the *peak* (U_p) and *valley* (U_v) voltages together with their uncertainties and the material the diode is made of knowing that typical valley voltages equal 0.7 V, 0.35 V and 0.45 V for gallium arsenide, germanium and silicon, respectively.

2. Determine energies of the E_n and E_p quasi Fermi levels (see fig. 3) from the following equations:

$$eU_p = \frac{1}{6}\Big[2E_p - E_n + \sqrt{(2E_p + E_n)^2 + 4E_pE_n}\Big]$$

$$eU_v = E_n + E_p$$

   where e denotes the electron charge.

   The above system of equations has two solutions:

$$\begin{cases} E_p = \frac{e}{2}\Big[U_v + 3U_p + \sqrt{U_v^2 + 2U_pU_v - 3U_p^2}\Big] \\ E_n = \frac{e}{2}\Big[U_v - 3U_p - \sqrt{U_v^2 + 2U_pU_v - 3U_p^2}\Big] \end{cases}$$

   and

$$\begin{cases} E_p = \frac{e}{2}\Big[U_v + 3U_p - \sqrt{U_v^2 + 2U_pU_v - 3U_p^2}\Big] \\ E_n = \frac{e}{2}\Big[U_v - 3U_p + \sqrt{U_v^2 + 2U_pU_v - 3U_p^2}\Big] \end{cases}$$

   Select a physically valid solution for further calculations.

3. Determine concentrations of the p- and n-type impurities using the equations:

$$n_d = \frac{2}{\sqrt{\pi}} N_c F_{\frac{1}{2}}(\varphi_d), \quad n_a = \frac{2}{\sqrt{\pi}} N_c F_{\frac{1}{2}}(\varphi_a)$$

$$\varphi_d = \frac{E_n}{kT}, \quad \varphi_a = \frac{E_p}{kT}$$

   T – temperature in Kelvin scale, k – Boltzmann constant, the values of Fermi–Dirac integral $F_{\frac{1}{2}}$ are shown in table 1 while the N_c constant is defined by equation:

$$N_c = 2C\Big(\frac{2\pi m_{ef} kT}{h^2}\Big)^{3/2}$$

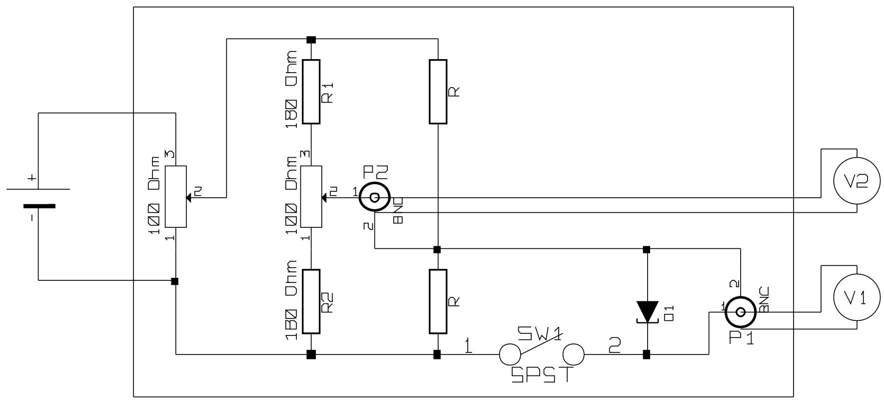

Figure 2: Electric circuit used to investigate a tunnel diode. The area limited by the rectangle is provided as a one module. Student's job is to connect voltmeters and power supply. The resistors R are dedicated for particular diode. The diode current is equal to the ratio of the voltage reported by the V2 voltmeter to a half of the resistance of resistor R.

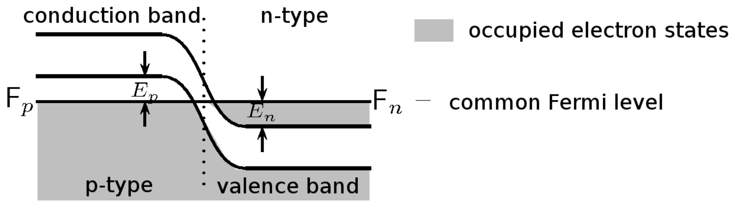

Figure 3: Quasi Fermi levels.

where: h – Planck constant, C – number of extremes in particular band (Ge: 4 for conduction band, 1 for valence band; Si: 6 for conduction band, 1 for valence band) while m_{ef} is an effective mass of dominant carrier. The effective mass is a product of the free electron mass and a coefficient which equals for Ge: $m_e = 0.22$, $m_h = 0.39$, for Si: $m_e = 0.33$, $m_h = 0.55$ and for AsGa: $m_e = 0.07$, $m_h = 0.66$ (m_e refers to electron while m_h to hole).

4. Comparison with critical concentrations

   An ideal intrinsic semiconductor has its Fermi level located close to the middle of energy gap between the valence and conductions bands (in fact the exact Fermi level position depends slightly on temperature). Doping with impurities shifts Fermi level towards the valence band (p-type semiconductor) or the conduction band (n-type semiconductor). A *critical concentration* is the concentration at which the Fermi level is located exactly at the top of valence band (p-type semiconductor) or at the bottom of conduction band (n-type semiconductor). For higher impurity concentrations the Fermi level is located within respective band (valence or conduction).

   Compare experimentally determined impurity concentrations with accepted values (Ge: $N_d = 8 * 10^{18} cm^{-3}$, $N_a = 4.7 * 10^{18} cm^{-3}$, Si: $N_d = 2.2 * 10^{19} cm^{-3}$, $N_a = 8 * 10^{18} cm^{-3}$, at $T = 300K$; d refers to donors while a to acceptors). Take into account uncertainties of experimantal results.

Table 1: Values of the Fermi-Dirac integral $F_{\frac{1}{2}}(x)$

x	$F_{1/2}(x)$	x	$F_{1/2}(x)$	x	$F_{1/2}(x)$
1.00	1.40	5.40	8.73	9.80	20.72
1.20	1.59	5.60	9.19	10.00	21.34
1.40	1.79	5.80	9.66	11.00	24.57
1.60	2.01	6.00	10.14	12.00	27.95
1.80	2.25	6.20	10.63	13.00	31.48
2.00	2.50	6.40	11.13	14.00	35.14
2.20	2.77	6.60	11.63	15.00	38.94
2.40	3.05	6.80	12.14	16.00	42.87
2.60	3.35	7.00	12.66	17.00	46.93
2.80	3.65	7.20	13.19	18.00	51.10
3.00	3.98	7.40	13.73	19.00	55.40
3.20	4.31	7.60	14.27	20.00	59.81
3.40	4.66	7.80	14.82	21.00	64.33
3.60	5.02	8.00	15.38	22.00	68.97
3.80	5.39	8.20	15.95	23.00	73.70
4.00	5.77	8.40	16.52	24.00	78.55
4.20	6.16	8.60	17.10	25.00	83.49
4.40	6.57	8.80	17.68	26.00	88.54
4.60	6.98	9.00	18.28	27.00	93.68
4.80	7.40	9.20	18.88	28.00	98.91
5.00	7.84	9.40	19.48	29.00	104.25
5.20	8.28	9.60	20.10	30.00	109.69

Appendix B

Determination of the e/k ratio from the $I_C(U_{BE})$ current-voltage characteristic of bipolar transistor

(Details of experiment and data analysis)

Experiment

1. Build electric circuit according to fig. 4. Do not switch on power supply.

2. Set power supply voltage to zero and switch on power supply. Increase gradually the voltage and observe collector current. Set the current limit of the power supply to such a value that the collector current does not exceed 10 mA. Such setting will prevent internal transistor structure from being heated by current flowing through transistor.

3. Before switching on temperature controller set the desired temperature to 30^{o}C and switch sensitivity of the temperature deviation indicator to the lowest possible value. Switch on temperature controller. Observe the temperature deviation indicator - its oscillations should decrease with time. Gradually increase sensitivity of the indicator. The temperature can be assumed as stable if the oscillations are within the displayed range while using maximum sensitivity of the indicator (the "0.001" range).

4. Write down the temperature reported by digital thermometer. Estimate its uncertainty. Collect the $I_C(U_{BE})$ characteristic (not less than 20 experimental points). While collecting the data take into account that I_C will be presented in the logarithmic scale. In order to have even distribution of experimental points it would be a good idea to make a $ln(I_C)$ vs. U_{BE} plot while collecting the data.

5. Collect the data each 10^{o}C up to 80^{o}C. If you have sufficient time you can also make measurements each 10^{o}C from 75^{o}C down to 35^{o}C. The rate of cooling can be accelerated by using electric fan. Wait for temperature stabilization after each temperature change.

Data analysis

1. Determination of the e/k ratio

   Make the $ln(I_C)$ vs. U_{BE} plot. Indicate different temperatures by different symbols/colors. For each selected temperature fit the data with linear regression.

   For an ideal transistor the slope coefficient s_T at temparature T equals $\frac{e}{k_B T}$. Make a second plot of s_T vs. T^{-1} and fit the data with linear regression (it is important to express temperature T in the Kelvin scale). The slope coefficient of the second plot should be equal to the $\frac{e}{k_B}$ ratio. Compare your experimental result with the accepted value. Discuss sources of possible systematic errors.

2. Determination of the experimental parameter m.

   Characteristic of a real bipolar transisitor shows some deviation from the ideal one. The deviation can be expressed by introduction of the experimental parameter m (see ref. [3]). Select one of the slope coefficients s_T (for example that found for the data collected at 30^o). Calculate the experimental parameter m using equation $m = \frac{e}{s_T k_B T}$ with e and k_B taken as accepted values and temperature T expressed in the Kelvin scale. Is m equal to 1? Discuss the value of your experimantal result.

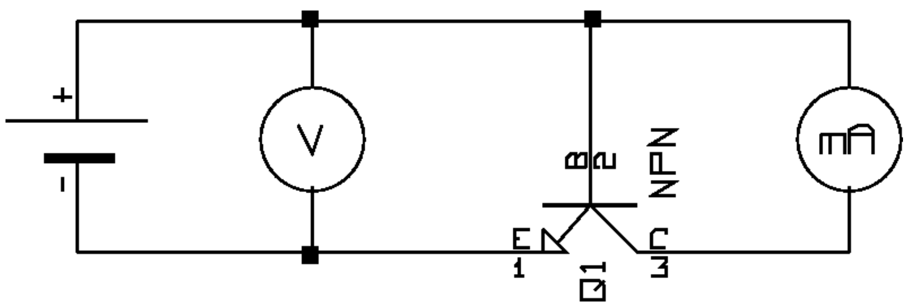

Figure 4: Electric circuit used to investigate a bipolar transistor (common base configuration).