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INVESTICE DO ROZVOJE VZDĚLÁVÁNÍ

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Physical laboratory 3

Task G Band gap width

Tasks

1. Determine the energy band gap of silicon and germanium using the photoelectric effect.

Introduction

Condensed or solid state materials can be generally divided into conductors and insulators. Conductors can be further divided into metals and semiconductors. The width of the electron band gap is considered one of the criteria for such division.

To understand the importance of semiconductors, we need to be aware of the relations between their fundamental properties and their real-world usage. The milestone for the description of the physical properties of semiconductors is the energy band model described by A. H. Wilson in 1931 [1]. The dependence of the electrical conductivity on the purity of the material with the possibility of doping the material with small concentrations of dopants, together with being able to influence their properties by external conditions (such as electric or magnetic field, temperature or radiation) lead to a large number of applications. Besides the electrical resistance's negative temperature coefficient, semiconductors are also characterised by exhibiting the photovoltaic effect, the diode effect, Zenner effect, or the photoelectric effect. The last-named effect is studied in this laboratory task.

Energy bands

A single isolated atom can only have discrete energy levels. However, as multiple atoms forming a condensed matter close together, their energy levels merge together forming the material's energy bands (figure 1). These energy bands are mutually divided by energy gaps called the energy band gaps. These correspond to energy intervals, where no electron of the corresponding energy can exist. Each energy band consists of many very close energy levels. Every state corresponding to these individual energy levels can be occupied by only a single electron as the Pauli exclusion principle describes it.

Insulators

In an insulator, the highest populated energy band is fully occupied, and it is divided from an unoccupied band by an energy band gap so wide that electrons can not be sufficiently thermally activated to jump from the full band to the unoccupied band.

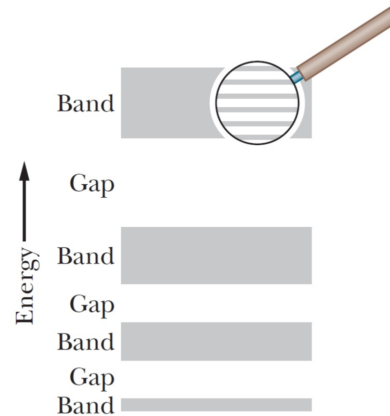

Figure 1: Band structure of a condensed matter. The magnified view shows that each band is formed from many close-lying energy levels. [2]

Metals

In metals, the highest occupied energy level falls somewhere near the middle of an energy band. It is said that the valence and conduction bands overlap. The band gap width is zero.

Semiconductors

The band structure of a semiconductor is similar to an insulator with the difference that the energy band gap (E_g) is significantly lower. A small number of electrons is thermally activated in a semiconductor such as silicon at the room temperature, and these electrons jump to the conduction band. In this way, the same number of holes is created in the valence band as is the number of electrons that jumped to the conduction band. Electrons and holes act as the charge carriers.

The number of electrons in the conduction band can be significantly increased by doping the semiconductor by e.g. small concentration of phosphorus, arsenic or antimony. This creates the n type doped semiconductor. The number of holes can be analogically increased by doping of the original semiconductor by e.g. boron. This creates the p type doped semiconductor.

p-n junction

The p-n junction is a semiconductor monocrystal with one part doped to form the p type material and the other part doped to form the n type material. The transition from one region to the other is perfectly sharp, occurring at a single junction plane. The following processes occur at this plane under thermal equilibrium:

1. The majority carriers (electrons on the n side and holes on the p side) diffuse through the junction plane. The motions of both the electrons and the holes contribute to a diffusive current.
2. The minority carriers (holes on the n side and electrons on the p side) are carried by the potential fall over the junction place and contribute to the drift current. At equilibrium, the average diffusion current that moves through the junction plane from the p side to the n side is balanced by an average drift current that moves in the opposite direction. These two currents cancel themselves out and the net current through the junction plane would be zero.
3. A charge carrier-depleted zone containing the immobile donor or acceptor ions forms in the area of the junction plane.

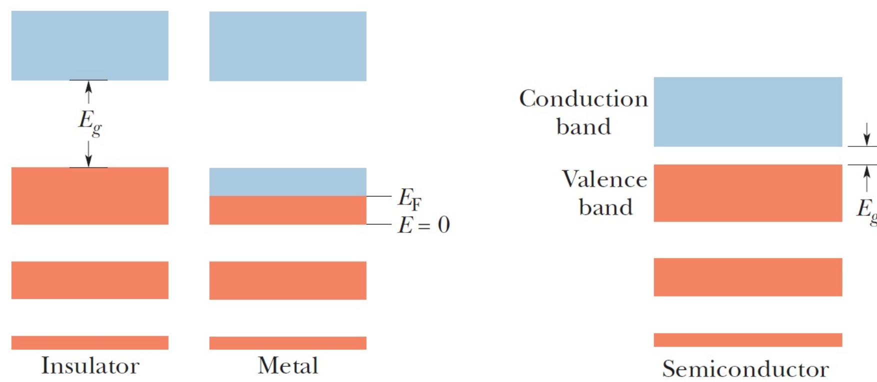

Figure 2: A schematic sketch of the band structure of an insulator is shown on the left. The levels occupied by electrons are shown in red. The highest occupied energy is lying on the top of a band, and the next free energy level is separated by a relatively large energy gap - the band gap E_g. The band structure of a metal is shown in the middle. The highest occupied energy level – the Fermi level E_F – is lying within a band. As free energy levels are located within the same energy band, electrons can easily change their energy levels within the whole band, leading to the electrical conduction. The energy structure of a semiconductor shown on the right is similar to that of an insulator, the band gap is, however, much narrower. The electrons are able to jump from the occupied to the unoccupied band through the thermal activation. [2]

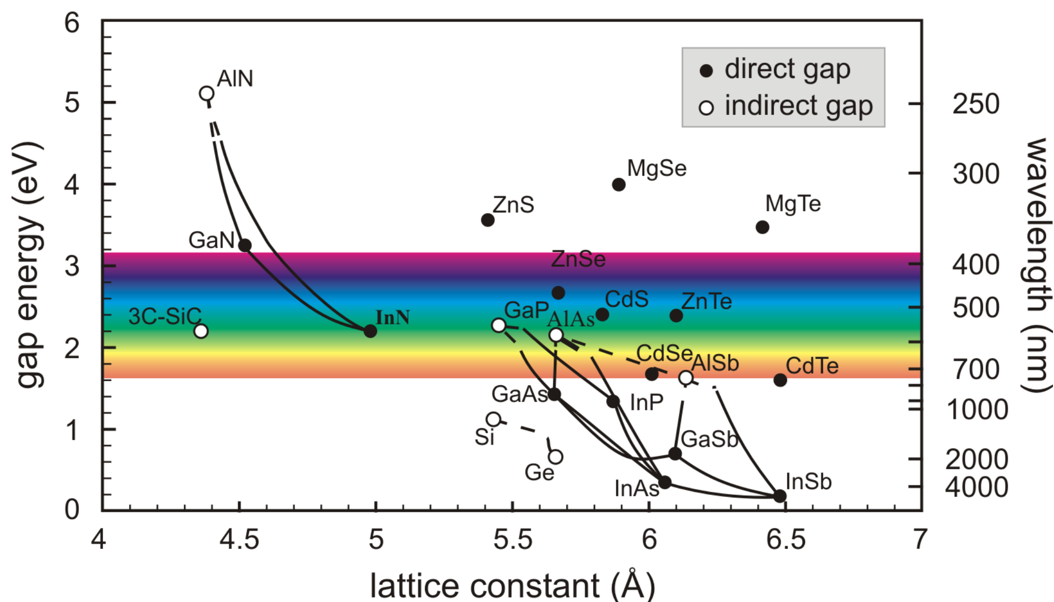

Figure 3: The band gap width and the lattice parameter of the most common elemental and compound semiconductors at room temperature. [3].

4. Contact voltage establishes over the depleted zone.

Photoelectric effect

The photoelectric effect is a physical effect where electrons are released (emitted) from the material because of the absorption of electromagnetic radiation (such as visible light). If these electrons are completely released from the material, the effect its called the *external photoelectric effect*. Suppose the electrons are not completely released from the material and instead remain as free conduction electrons in a higher energy band. In that case, we are talking about the *internal photoelectric effect*.

Generation of free conduction electrons by the electromagnetic radiation takes place if the photon energy is equal to or higher than the band gap width. If this condition is fulfilled, electrons are released from the valence band into the conduction band. If this occurs in the vicinity of the p-n junction, these excessive (from the point of thermodynamic equilibrium) charge carriers are divided by the inner electric field. Electrons flow towards the n type material and holes towards the p type material. This leads to the alteration of the charge in the volume of the material in the p-n junction's vicinity compared to the case without the excessive charge carriers' external generation. This results in a change of the electric field in the said area and the so-called photovoltage arises over the p-n junction. The generated photovoltage depends on the way of its generation and the radiation intensity.

Measurement method principle

We will measure the photoelectric effect on a silicon and germanium photodiode. A photodiode is a semiconductor device containing the p-n junction, and it is used to transform an optical signal to an electric signal. For this, it uses the photoelectric effect. A cross-section of one type of a photodiode is schematically shown in figure 4a. A p type area is made by a dopant diffusion in the base n type silicon material. Therefore, a p-n junction is created. Electrical contacts are present in both the p type and the n type areas. The diode surface is protected by a SiO_2 coating. The whole device is usually encased in resin forming the outer case of the diode.

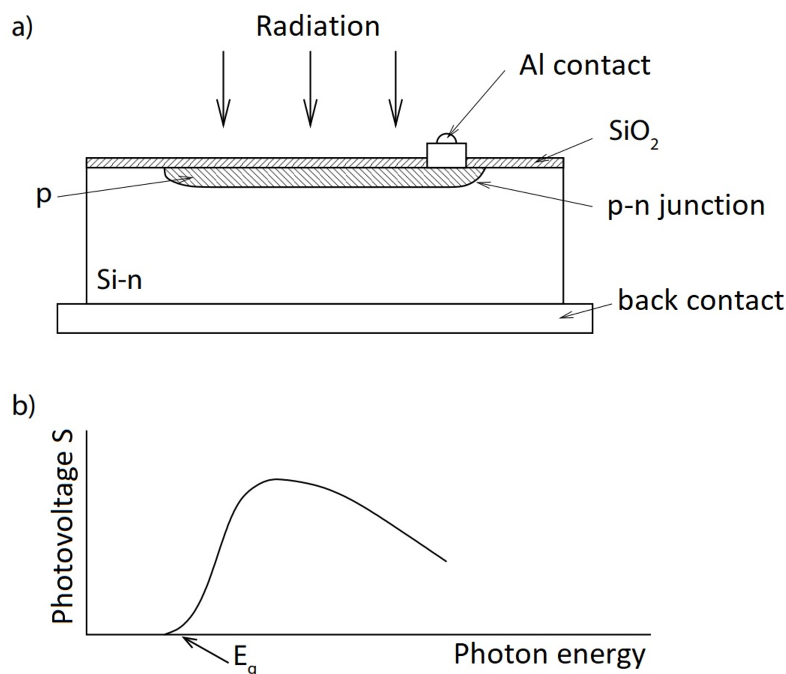

Figure 4: (a) A photodiode schematic; (b) The dependence of the photovoltage on the photon energy.

Radiation of different wavelength is absorbed in different thickness of the semiconductor. Therefore, the p type material's thickness needs to be such that the used radiation is absorbed in the p-n junction's vicinity. The intensity of the radiation intensity in the material is mathematically described as

$$I(x) = I_0 R \, \mathrm{e}^{-\alpha x}, \tag{1}$$

where $I(x)$ is the intensity in depth x under the surface, R is the optical reflectivity of the surface and α is the absorption coefficient. You can see that the intensity of the radiation exponentially decreases with depth.

Suppose photons with a too high wavelength not having high enough energy for excitation of electrons into the conduction band (i.e. creation of conduction electron and a hole in the valence band) are used. In that case, the radiation passes through the material with a low absorption coefficient. The internal photoeffect can occur as the wavelength is sufficiently decreased to correspond the energy E_g.
The absorption coefficient increases with the decreasing wavelength, and the number of photons that can be absorbed in the vicinity of the p-n junction increases as well. Therefore, the photovoltage first increases with the increasing absorption coefficient. However, it reaches its maximum, and it then decreases as more and more electron-hole pairs are created just under the surface of the photodiode (therefore far from the p-n junction) – see figure 4b.

The band gap width E_g is determined from the spectral dependence of the photovoltage per one photon $S(\lambda)$; that is the relation of the ratio of the measured photovoltage $U(\lambda)$ and the number of incoming photons $N(\lambda)$ on the wavelength:

$$S(\lambda) = \frac{U(\lambda)}{N(\lambda)} \tag{2}$$

The band gap width can then be determined from the photon energy for which the photodiode starts to be sensitive, i.e. for which the photovoltage $U(\lambda)$ on the p-n junction is detected (see fig. 4b). It needs to be considered that photons with high wavelength cannot excite conduction electrons and do not contribute to the photoeffect.

Experimental setup

The experimental configuration (obr. 5) consists of two main parts. These are the optical setup and the device for the measurement of low voltages. In the optical setup, light from a halogen lamp passes through an optical route through an input slit to a monochromator. A monochromatic ray then passes through an output slit to the photodiode. Narrower slits lead to a lower intensity light, but they also provide higher spectral resolution. On the other hand, wide-opened slits provide high intensity but worse monochromaticity of the light. The individual semiconductor photodiodes (silicon and germanium) are interchangeable. It is necessary to pay attention to the light being aimed at the photodiode's active area, where the voltage, measured by a sensitive voltmeter, is generated.

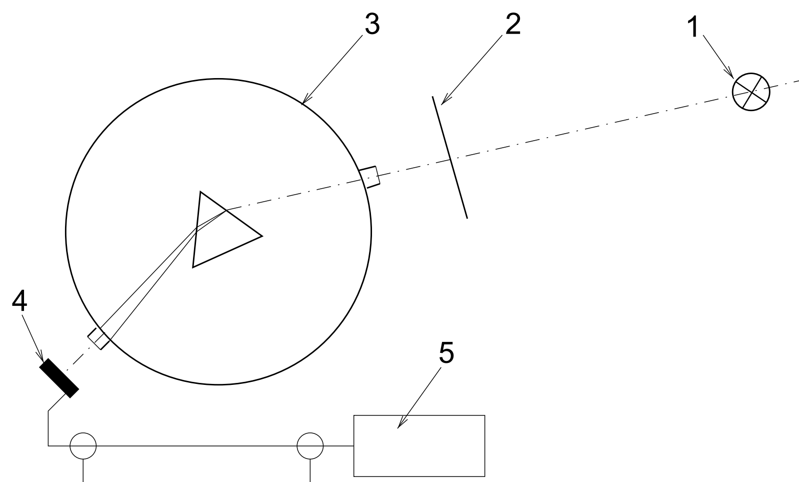

Figure 5: Experimental setup: 1 - Halogen lamp, 2 - Convex lens, 3 - Monochromator, 4 - Semiconductor photodiode, 5 - Voltmeter.

Figure 6: Measurement setup: 1 - Voltmeter, 2 - Monochromator, 3 - Lamp, 4 - Lamp voltage source, 5 - Photodiode cover.

Experimental procedure

1. Familiarise yourselves with the measurement setup as per figure 5.
2. Use both the silicon and germanium photodiodes for the measurements.
3. Aim the light on the active area of the photodiode during the measurement.
4. Set the monochromator slits and the voltmeter range in a way to achieve the highest possible monochromaticity of the light while using the whole range of the voltmeter.
5. For each diode measure the dependence $U = f(\lambda)$.
   (a) Using the table at the end of the manual find the values of $D(\lambda) \propto N(\lambda)$ for those wavelengths used for the measuring of $U(\lambda)$.
   (b) For each wavelength λ determine the ralative value of $S(\lambda)$ according to equation (2).
6. For each wavelength calculate the photon energy.
7. Plot the dependence $S = f(E)$ into a graph and determine the band gap width E_g for the first non-zero value.

References

[1] Frank H.: Fyzika a technika polovodičů, SNTL, 1990

[2] Jearl Walker, David Halliday, Robert Resnick: Fundamentals of physics. 10th edition. Wiley, 2014, ISBN 978-1-118-23072-5

[3] Ibach H. a Lueth H.: Solid-State Physics, Springer Verlag, 2003

Appendix

Spectral radiation of the halogen lamp.

Halogen lamp spectral radiation intensity				
$D = f(\lambda)$				
λ (nm)	D		λ (nm)	D
1000	158		1500	110
1100	140		1600	95
1150	135		1700	70
1250	125		1800	46
1350	120		1850	35
1400	115		1900	15

Relative intensity of the photodetector signal (D) used for the measurement of the spectral distribution of the radiation of the halogen lamp. This value is directly proportional to the number of photons passing through the monochromator and therefore to the number of photons arriving at the photodiode (N).