SEMICONDUCTOR DIODE

Semiconductor diode is an electronic element made of different types of extrinsic semiconductor: N-type semiconductor doped by donor impurities and P-type semiconductor doped by acceptor impurities.

Free carriers of electric charge are present in both N- and P-type semiconductors in broad interval of temperatures. In P-type, majority free charge carriers are holes, while minority charge carriers are electrons. Inside the crystal lattice, fixed negative acceptor ions of impurity can be found. In N-type, the reverse is true: positive donor ions of impurity are fixed inside the crystal lattice, while majority charge carriers are electrons and minority charge carriers are holes.

Unbiased (non-polarized) PN junction

When P- and N-type semiconductors are in electric contact, diffusion of majority charge carriers takes place from the region of high to the region of lower concentration. This means that the electrons, as majority charge carriers in N-type semiconductor, move from N side of the junction to the P side, while holes, as majority charge carriers in P-type semiconductor, moves from P to N side of the junction. In doing so, holes meet a large number of free electrons during the diffusion process, they collide and recombine. The same is true for free electrons – they collide and recombine with the holes during the diffusion from N- to P-type semiconductor.

The result is formation of a depletion region around the PN junction in which free charge carriers are absent due to the recombination. Consequently, negative fixed charge (acceptor ions) is present on the P side of the junction, and positive fixed charge (donor ions) on the N side of the junction. These ions cannot move as they are fixed inside the crystal lattice. So, opposite electric charge is found at the opposite sides of the PN junction, which causes the electric field and establishes potential barrier on PN junction. The area in which there are no free charge carriers and only fixed charge from acceptor and donor ion is present, is called PN barrier or depletion zone (region).

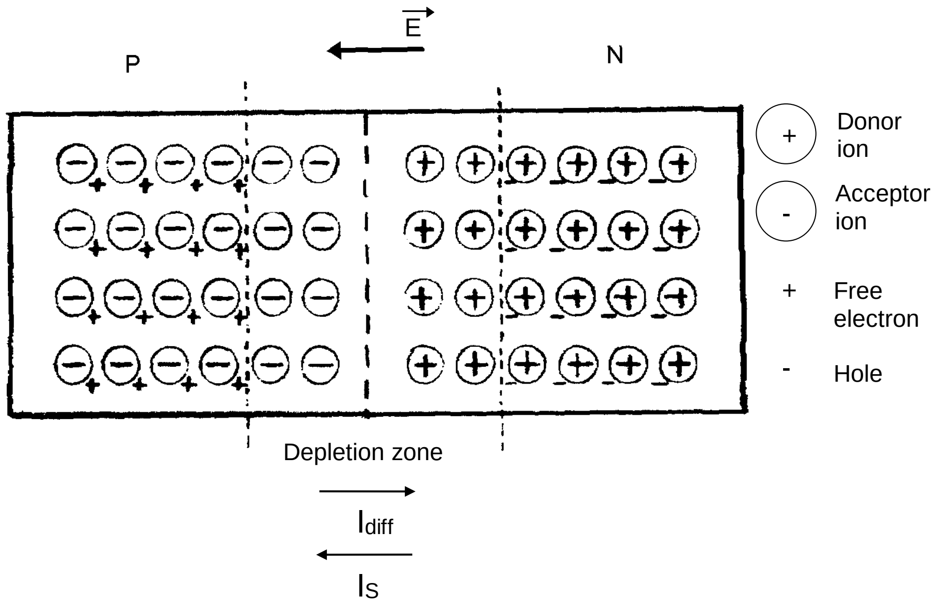
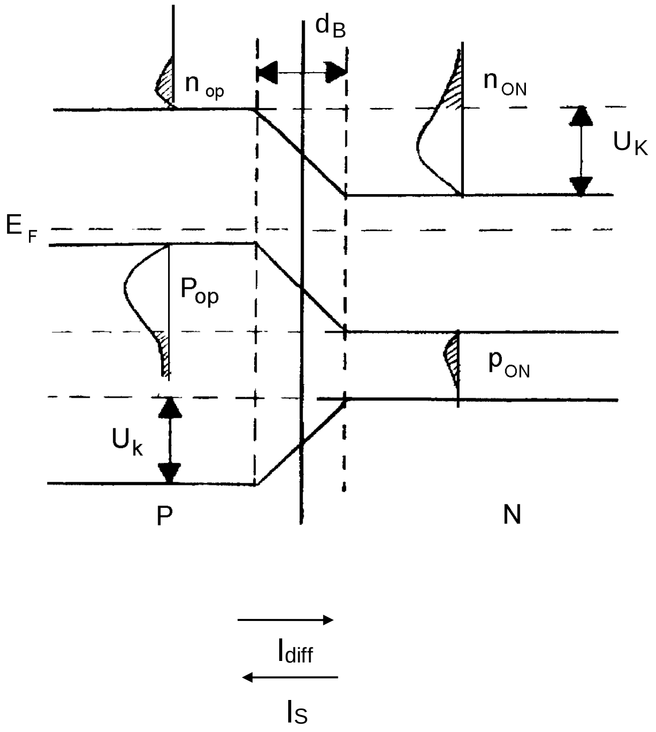


Figure 1. *Unbiased (non-polarized) PN junction*

So, electric field is established across the depletion region of unbiased (non-polarized) PN junction. PN junction is unbiased if no outer voltage is applied. This electric field opposes the diffusion of majority charge carriers (fig. 1). Beside the majority charge carriers, minority charge carriers (electrons in P semiconductor and holes in N semiconductor) are also present in semiconductor. The electric field across the PN junction accelerates the minority charge carriers across the depletion zone and forms drift current of minority charge carriers. On the contrary, diffusion current is caused by majority charge carriers and flows in the opposite direction to the drift current (fig. 1).

The majority free charge concentration is changed in each of the semiconductor types due to the diffusion between P and N sides of the PN junction, which also changes the Fermi level. The flow of free charge takes place until the equilibrium has been reached and the Fermi levels equalize in both semiconductor types. In equilibrium, diffusion and drift currents are the same and in opposite direction, so there is no net current through the PN junction.

Figure 2 shows energy diagram of PN junction in equilibrium. Shadowed areas under the curves of Fermi distribution correspond to the number of free charge carriers that flow by diffusion and drift between the two semiconductor types in PN junction. In equilibrium, these number of charge carriers for each semiconductor types on P and N side of the junction are the same, so the net current vanishes.



- n_{oP} – equilibrium electron concentration on P side
- n_{oN} – equilibrium electron concentration on N side
- p_{oP} – equilibrium hole concentration on P side
- p_{oN} – equilibrium hole concentration on N side
- d_B – barrier width (width of depletion zone)
- U_K – barrier height
- E_F – Fermi level

Figure 2. *Potential barrier on unbiased PN junction and energy diagram*

Potential electrostatic barrier between P and N side of the junction does not affect minority charge carriers that make drift current. Consequently, drift current does not depend on the barrier height and depends on temperature as the minority charge carriers are formed in pair-generation processes due to the thermal breakdown of covalent bonds. Drift current I_S is constant for a constant temperature and equal to the sum of contributions of both electron I_{Sn} and hole I_{Sp} drift components:

$$I_S = I_{Sn} + I_{Sp}$$

On the other hand, diffusion current depends on potential barrier height. For a higher barrier, less majority charge carriers have sufficient energy to overcome it and the diffusion current lessens.

Biased (polarised) PN junction

PN junction can be biased by applying an external voltage at the ends of the two semiconductor types. P side can be connected to the positive or negative side of this voltage. If the negative side of external voltage is applied to the N side of the PN junction, and positive side to the P side of the PN junction, the bias becomes **forward bias**. The height of the potential barrier is lowered, more majority charge carriers can pass through the PN junction and the diffusion current increases dramatically. If the negative side of the external voltage is applied to the P-type semiconductor, and positive side to the N-type semiconductor, the potential barriers increases and the bias becomes **reverse bias**. This in turn decreases diffusion current to the level where it becomes negligible, and only very small constant drift current is present. Such a PN junction is called **semiconductor diode**.

Current *I* through the PN junction consists of both diffusion and drift components and varies with the external voltage *U* regardless its sign:

$$I = I_S\left(e^{\frac{qU}{kT}} - 1\right) \qquad (1)$$

External voltage *U* is positive in forward bias and the total current rises exponentially with increased external voltage. External voltage is negative in reverse bias and exponential term in (1) can be neglected compared to the 1, even for small negative external voltages at a room temperature. So, the total current in reverse biased PN junction is I_S and corresponds to the current of the minority charge carriers which does not depend on the external voltage. The current I_S is called reverse bias current and assume very low values of the order of μA – nA at the room temperature.

Diagram that shows relation (1) is called I-U characteristic of ideal semiconductor diode (fig. 3).

Very small, constant reverse bias current for negative external voltage means that the resistance of the diode is very high in the reverse bias. On the contrary, very large exponential increase of the forward bias current for increased and positive external voltage implies low resistance of the diode in forward bias. This large difference in resistance between reverse and forward bias means that semiconductor diode as an electronic element have rectifying properties and can be used as a rectifier, which is one of the major application of diode in electronic circuits. As can be seen, diode will forward current only in one direction, and block it in the opposite one.

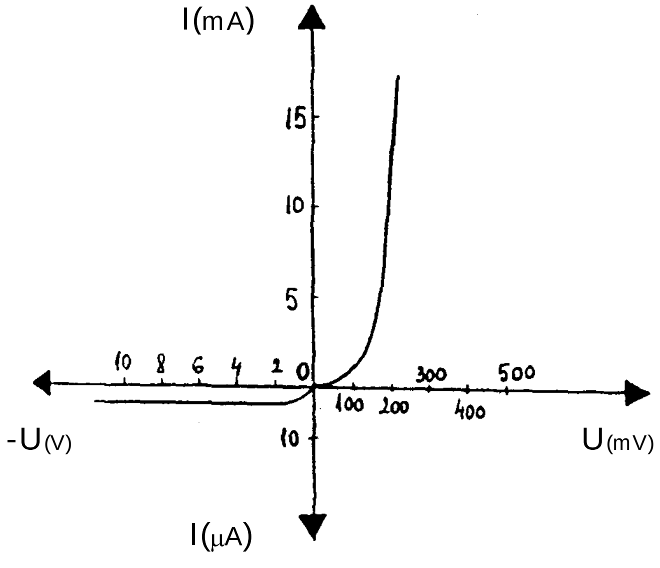
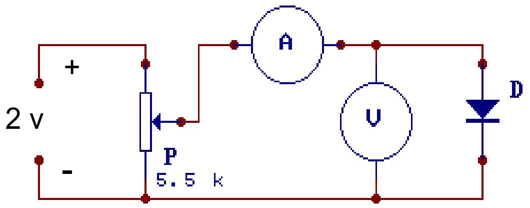


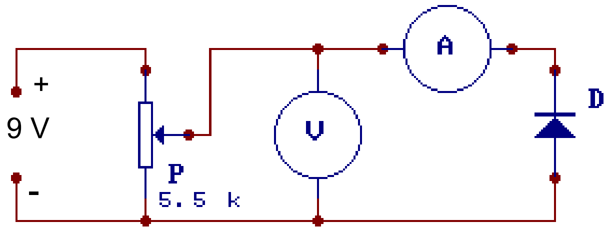
Figure 3. *I-U characteristic of ideal semiconductor diode.*

ASSIGNMENT I:

1. Assembly the electric circuit with a semiconductor diode in forward and reverse bias as shown below. Measure the dependence of diode current on applied external voltage and determine I-U characteristic of two semiconductor diodes. Obtain the measurements for both silicon and germanium diodes.



Forward bias



Reverse bias

2. Based on your measurements, which semiconductor material (silicon or germanium) makes diode a better rectifier?

Notes:

- Pay attention how the instruments are connected in the circuit due to their imperfection! They should be connected differently in forward and reverse bias as shown on above figures.
- Pay attention to the maximum allowed currents in forward bias:
  Germanium diode AY 102 I_{max} = 500 µA
  Silicon diode BY 238 I_{max} = 500 mA
- Vary external voltage in reverse bias up to - 8 V.

ENERGY WIDTH OF FORBIDDEN BAND IN SEMICONDUCTOR DIODE

Semiconductors, as well as all crystalline solid materials, have characteristic band energy structure. Atoms in crystal lattice are in interaction due to the finite distance between them. This causes splitting of discrete energy levels of *N* individual atom into *N* closely spaced allowed energy levels. These levels are so closely spaced that they can be considered continuous and can be well approximated by continuous energy band instead of a large number of discrete energy levels. Three such bands are of importance for electric conductivity of semiconductors: valence, forbidden and conduction bands (fig. 1). Valence band has lower energy than conduction band, with a forbidden ban in-between.

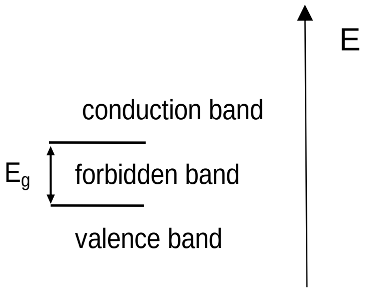


Figure 1. *Energy band structure of a semiconductor*

There are no free charge carriers in a semiconductor at absolute zero as all electrons are bound in electronic doublets which form covalent bond between atoms in the crystal. All available allowed energy states are filled up to the Fermi level and are found in the valence band. At this temperature, all energy states in the conductive band are empty. As the temperature increases above zero, some covalent bonds break down and electrons move from valence to the conductive band, thus becoming free charge inside the crystal lattice. Conductive band is separated from valence band with forbidden band where no energy states are allowed. In order for an electron to move from valence to conductive band, it must have energy larger than the width of the forbidden band as there are no allowed energy states in the forbidden band. Statistically, the probability ***f*** for a transition of an electron from valence to conductive band for a given electron energy *kT* drops exponentially with the width E_g of the forbidden band.

$$f \propto e^{-\frac{E_g}{kT}}$$

Electric conductivity of the material on a given temperature *T* will be larger for a smaller energy width of the forbidden band. This width is around 1 eV in semiconductors.

Width of forbidden band can be experimentally determined by measuring dependence of the reverse bias current of semiconductor diode I_S on the temperature. Reverse bias current is a drift current of minority charge carriers which are generated by breaking down covalent bonds. This process is temperature dependent – higher temperature causes more covalent bonds to break, generating more minority charge carriers and increasing the reverse bias current. So, reverse bias current is temperature dependent and can be measured in reverse bias PN junction where it is the only current component that flows though the PN junction (diffusion current of majority charge carriers is negligible).

External voltage *U* is negative (*U* < 0) in reverse bias, so it can be shown from the equation of I-U characteristic of an ideal diode

$$I = I_S\left(e^{\frac{qU}{kT}} - 1\right) \qquad (1)$$

that the current through the diode is independent of the external voltage for $|U| \gg \frac{kT}{q}$ and equal to:

$$I = -I_S$$

At the room temperature, external voltage should be only $|U| \sim 0.1$ V in order for the exponential term in (1) to become negligible and much less than one. Reverse bias current depends on the properties of semiconductor material and charge carriers (electrons and holes) and on intrinsic concentration of charge carriers which in turn depends on temperature:

$$I_S = Sqn_i^2\left(\frac{D_p}{N_D L_p} + \frac{D_n}{N_A L_n}\right) \qquad (2)$$

where:

n_i^2 - intrinsic concentration of charge carriers (electrons and holes):

$$n_i^2 = CT^3 e^{-\frac{E_g}{kT}} \qquad (3)$$

C - quantity that is not dependant significantly on the semiconductor material and can be considered constant
S - surface area of the PN junction through which the current can flow
T - absolute temperature
E_g - energy width of the forbidden band
D_p – diffusion constant of the hole
D_n – diffusion constant of the electron
L_p - diffusion length of the hole
L_n - diffusion length of the electron
N_D - concentration of donor impurities
N_A – concentration of acceptor impurities
k - Boltzmann constant

From (2) and (3) follows:

$$I_S = SqCT^3 e^{-\frac{E_g}{kT}}\left(\frac{D_p}{N_D L_p} + \frac{D_n}{N_A L_n}\right) \qquad (4)$$

Width E_g of forbidden band, diffusion lengths *L* and diffusion constants *D* depend on the temperature much less than the term $T^3 e^{-\frac{E_g}{kT}}$, so their temperature dependence can be approximately neglected. Relation (4) now becomes:

$$I_S = KT^3 e^{-\frac{E_g}{kT}} \qquad (5)$$

where all terms from relation (4) that approximately do not depend on temperature are grouped together into constant *K*.

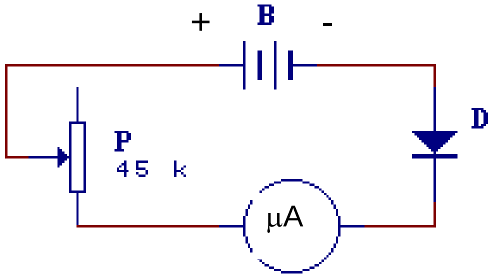
Further:

$$\ln\frac{I_S}{T^3} = \ln K - \frac{E_g}{kT} \qquad (6)$$

Function $\ln\frac{I_S}{T^3} = f\left(\frac{1}{T}\right)$ is now a linear regression with the slope coefficient $-\frac{E_g}{kT}$. Energy width E_g of the forbidden band can be determined by measuring dependence of the reverse bias current on the temperature, $I_S = f(T)$. If the least-square fitting is used, slope coefficient can be obtained and energy width of the forbidden band determined.

ASSIGNMENT II:

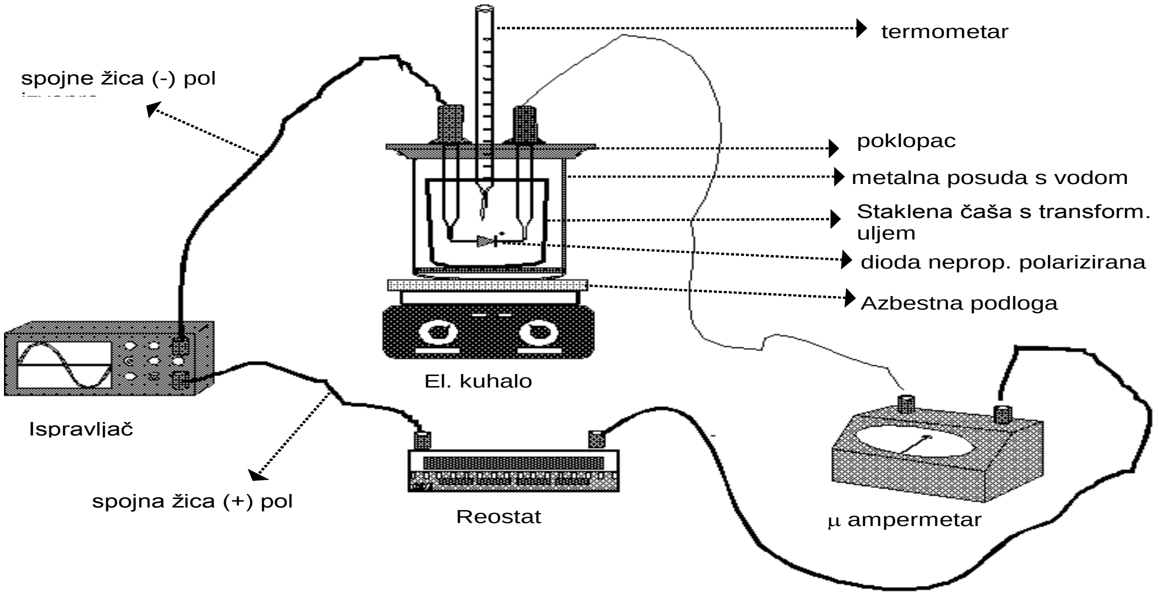
1. Determine the energy width E_g of the forbidden band for a given semiconductor. Use the semiconductor diode in the circuit shown below.



2. Determine energy width of the forbidden band by the use of the least-square method. Determine uncertainty of the energy width of the forbidden band from the uncertainty of the slope coefficient obtained by least-square fitting.

Notes:

- Use the largest resistance on the potentiometer before applying the voltage in the circuit. Increase slowly voltage from minimum to larger values. Then lower the resistance to minimum, while keep the voltage at the value on which the instrument measure the current of ≤ 1 μA. Do not change the voltage anymore, and proceed to heat the diode. Measure the temperature for every reverse bias current increase of 0.5 μA.
- Dependence of $\ln(I_S/T^3)$ on $(1/T) \cdot 10^{-3}$ (K^{-1}) can be shown on a diagram.
- Measurements are obtained by submerging diode and thermometer into transformer oil as shown on the figure below. Transformer oil is an excellent electric insulator and good thermal conductor.
- Container with the transformer oil is submerged inside a larger container with the water. The water is used to heat the transformer oil up to the maximal temperature of 100 °C. Diode made of silicon can withstand temperatures up to 150 °C. Diode made of germanium is not suited for such measurement as it can withstand temperatures of no more than 70 °C.


termometar
spojne žica (-) pol
poklopac
metalna posuda s vodom
Staklena čaša s transform. uljem
dioda neprop. polarizirana
Azbestna podloga
El. kuhalo
Ispravljač
spojna žica (+) pol
Reostat
μ ampermetar