Politechnika Wrocławska
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Laboratorium
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Exercise 48

DETERMINATION OF PLANCK CONSTANT BASED ON CURRENT-VOLTAGE CHARACTERISTICS OF LEDS

Key words: Planck constant, Light Emitting Diodes (LEDs), p-n junctions (semiconductor junctions), current – voltage characteristics of p-n junction

Abstract: Experimental determination of Planck's constant **h = 6.626×10−34 [J·s]** is performed using Light Emitting Diodes (LEDs). Spectrophotometry and basic circuit analysis techniques are employed to obtain empirical data with respect to the energy of emitted photons and used to calculated Planck's constant.

1. Introduction – Planck theory

The concept of energy being transferred only in discrete packets called quanta is a fundament of the revolution in physics started by a German scientist Max Planck. Towards the end of the 19th century the classical theory of black body radiation was proving inadequate, as evidenced by what is known today as the ultraviolet catastrophe. According to classical physics, the ideal black body at thermal equilibrium should emit radiation in all frequency ranges, emitting more energy as the frequency increases. The total amount of thus radiated energy would be infinite, contradicting the principles of conservation of energy. In October of 1900 Planck developed his black body formula, solving the issue of infinite energy, marking the true start of a quantum theory. Planck's original formula was:

$$I(\lambda,T)=\frac{2\pi\cdot c\cdot h}{\lambda^5}\cdot\left(\frac{1}{\exp\left(\frac{h\cdot c}{k_B T\cdot\lambda}\right)-1}\right) \tag{1}$$

where: *c* – velocity of light in vacuum, *h* – Planck's constant, *λ* – wavelength, k_B - Boltzmann's constant, *T* – temperature measured in Kelvins.
The significance of Planck's theory is that 'quantum' (small packet of energy) can be determined by frequency of the radiation and Planck's constant. It describes the behaviour of particles and waves at atomic level as well as the corpuscular nature of light.

2. Light Emitting Diodes (LEDs)

Light Emitting Diodes (LEDs) are semiconductor devices defined by their ability to emit electromagnetic radiation in the visible spectrum when sufficient bias is applied. LEDs are composed of p-type (acceptor) and n-type (donor) materials that form a physical system referred to as a p-n junction.
What are n-type or p-type semiconductors? If the crystalline array of silicon (with four valence electrons) is "doped" (mixed with an impurity) with arsenic, which has five valence electrons, its electronic property will change. Four bonds will still be formed but there will

be a leftover electron that can wander through the crystal. This is called an n-type semiconductor. Fig. 1 presents the scheme of bonding of atoms in the crystal lattice of n – type semiconductor (Si doped with As atoms).

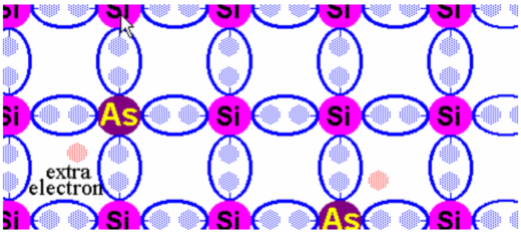


Fig. 1. Scheme of bonding of atoms in the crystal lattice of n – type semiconductor.

Boron can also be used to dope a pure crystal of silicon. But since boron only offers three of the four electrons that a silicon atom needs, each silicon center is left with a hole. This is called p-type doping. Fig. 2 shows an example of bonding of atoms in the crystal lattice of p – type semiconductor (Si doped with B atoms).

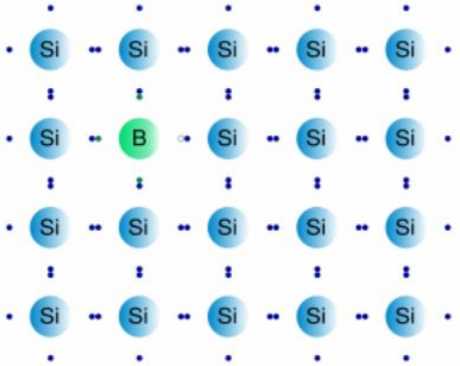


Fig. 2. Scheme of bonding of atoms in the crystal lattice of p – type semiconductor.

Pure silicon is an example of an **intrinsic semiconductor**. Silicon doped with arsenic (or any other element of a group V) creates p-type semiconductor, which means that As is a **donor dopant** for Si because it introduces additional valence electrons into the material. These additional electrons are bound only weakly to their parent impurity atoms, and even at very low temperatures these electrons can be promoted into the conduction band of the semiconductor. This is often represented schematically in band diagrams by the addition of '**donor levels**' just below the bottom of the conduction band, as in the schematic below.

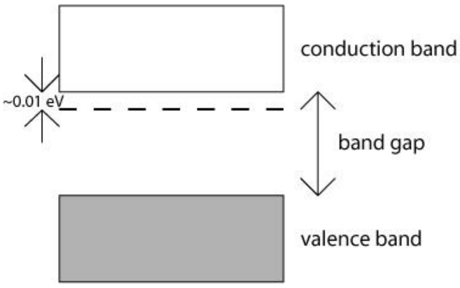


Fig. 3. Band diagram of a n-type semiconductor.

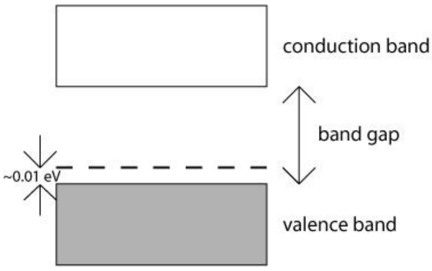
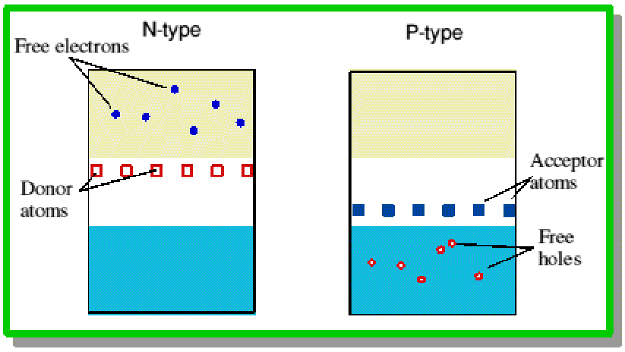


Fig. 4. Band diagram of a p-type semiconductor.

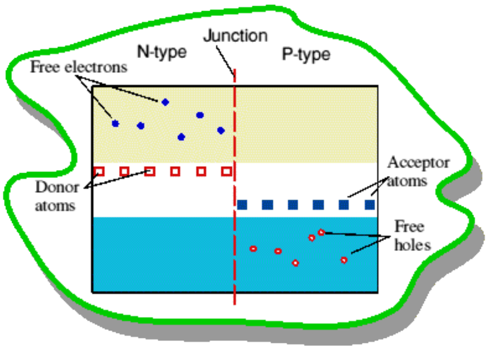
Semiconductors that have been doped in this way will have a surplus of electrons, and are called ***n*-type semiconductors**. In such semiconductors, electrons are the majority carriers.

Analogically, silicon doped with boron (or any other element of a group III) creates a p-type semiconductor, what means that B is an **acceptor dopant** for Si. There will be a deficit in the number of valence electrons in the material. This introduces electron-accepting levels just above the top of the valence band, and causes more holes to be introduced into the valence band. Hence, the majority charge carriers are positive holes in this case. Semiconductors doped in this way are termed ***p*-type semiconductors**. Fig. 4 presents a band diagram of a p-type semiconductor.

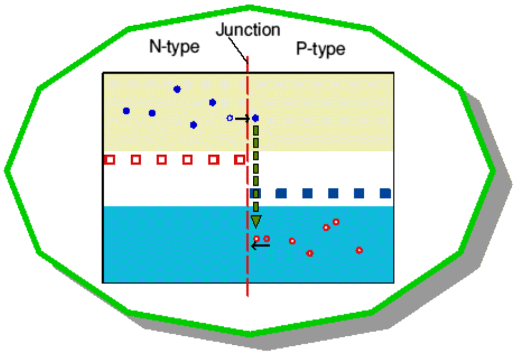
Now, if we take two semiconductors of different conductivity, p-type and n-type, and we combine these materials together we get the **p-n junction**. To understand how a p-n junction works, begin by imagining two separate bits of semiconductor, one n-type, the other p-type, as shown below:



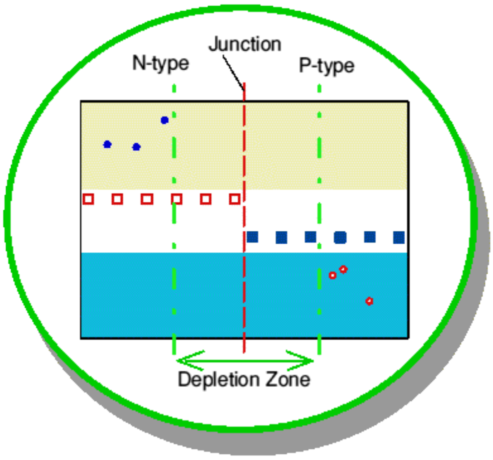
The combination of the semiconductors creates of p-n junction, as shown below:



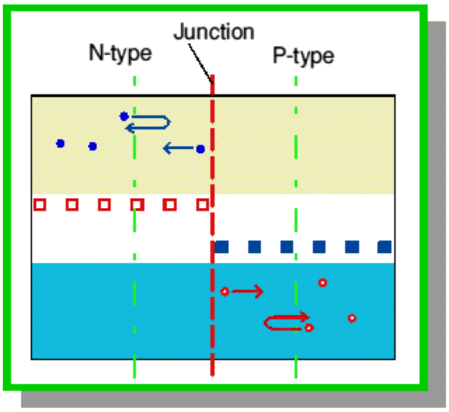
After combination of two different semiconductors free electrons on the n-side and free holes on the p-side can initially wander across the junction. When a free electron meets a free hole it can 'drop into it'. So far as charge movements are concerned this means that the hole and electron cancel each other and vanish – see the schematic below:



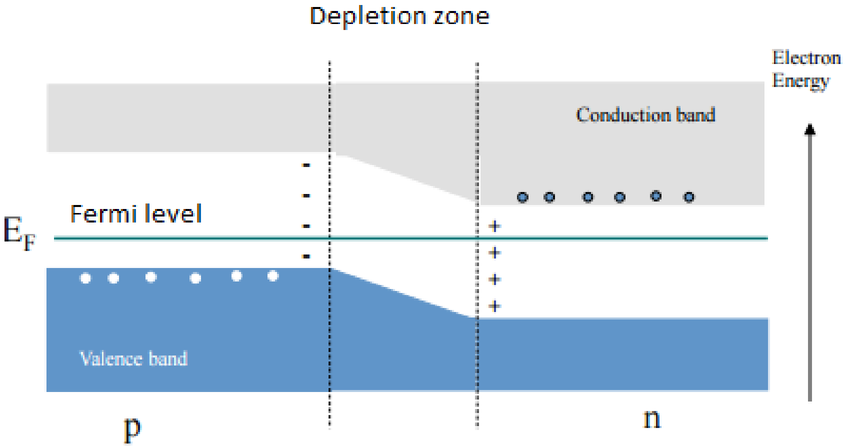
As a result, free electrons and holes near the junction tend to anihilate each other, producing a region depleted of any moving charges. This creates what is called the **depletion zone** – see the picture below:



Now, any free charge which wanders into the depletion zone finds itself in a region with no other free charges. Locally it sees a lot of positive charges (the donor atoms) on the n-type side and a lot of negative charges (the acceptor atoms) on the p-type side. These exert a force on the free charge, driving it back to its 'own side' of the junction away from the depletion zone.



The diffusion of carriers continues until the thermal equilibrium is reached. After that the p-n junction forms, as shown in the schematic picture below:



A p-n junction forms the simplest semiconductor device – a diode, which allows current flow in one direction only.

3. Current – voltage characteristic of a diode (p-n junction)

If a sufficient positive voltage (forward bias) is applied between the two ends of the p-n junction, it can supply free electrons an d holes with extra energy that they require to cross the junction as the width of the depletion layer around the p-n junction is decreased, as shown in Fig. 5.

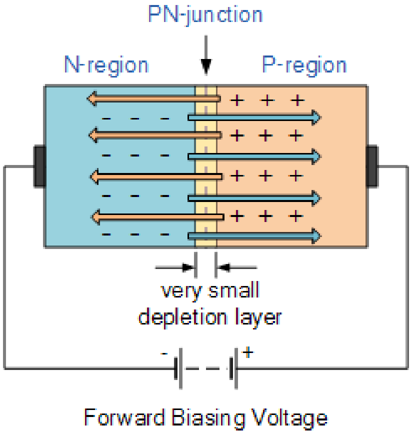


Fig. 5. Polarization of a p-n junction in the forward direction.

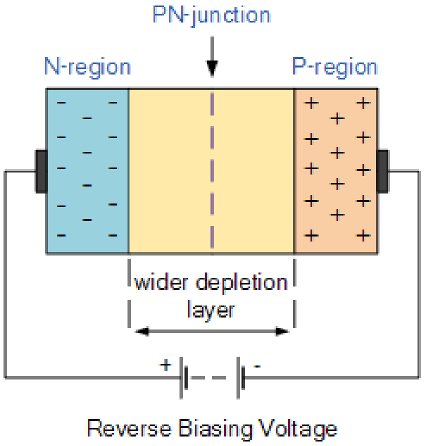


Fig. 6. Polarization of a p-n junction in the reverse direction.

Applying a negative voltage (reverse bias) results in the free charges being pulled away from the junction, increasing the depletion layer width. This has the effect of increasing the effective resistance of the junction itself thus blocking current flow through the diode (see Fig. 6).

One can measure current when applying the external voltage to the diode polarazing it in the reverse or forward direction. A typical current-voltage (I-V) characteristic for the diode looks as follows (Fig. 7):

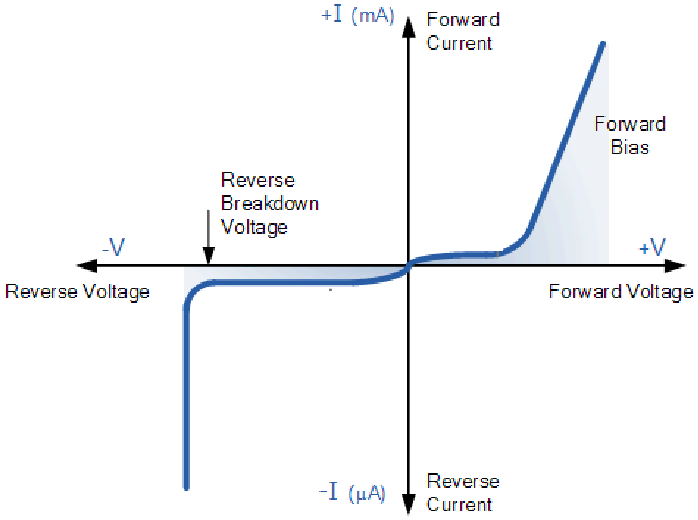


Fig. 7. I-V characteristic of a diode (p-n junction).

4. Determining of the Planck constant from the I-V characteristic of LED

When we connect the LED to an external voltage in the forward bias direction, the height of potential barrier across the p-n junction is reduced (see Fig. 8a). At a particular voltage the height of the potential barrier becomes very low and the LED starts glowing, i.e. in the forward biased condition electrons crossing the junction recombine with the holes moving in the opposite direction and the excess energy is emitted as photons. The light energy emitted during forward biasing of LED is given by the equation:

$$E = \frac{h \cdot c}{\lambda} \tag{2}$$

The relationship between the light energy emitted from LED and the applied voltage is the following:

$$E = e \cdot U_b \tag{3}$$

where e = 1.602 × 10^{-19} C is the magnitude of the electron charge, U_b – a voltage referring to the potential barrier of a diode, determined from the I-V curve (cf. Fig. 8b).
The experimental determination of Planck's constant is then easily obtained by measuring the wavelength of the emitted radiation from an LED and applied voltage over the LED concurrently, combining equations (2) and (3) to get h:

$$\frac{h \cdot c}{\lambda} = e \cdot U_b \tag{4}$$

Rearranging Eq. 4 we get:

$$h = \frac{e}{c} \cdot \lambda \cdot U_b . \tag{5}$$

(a) (b)

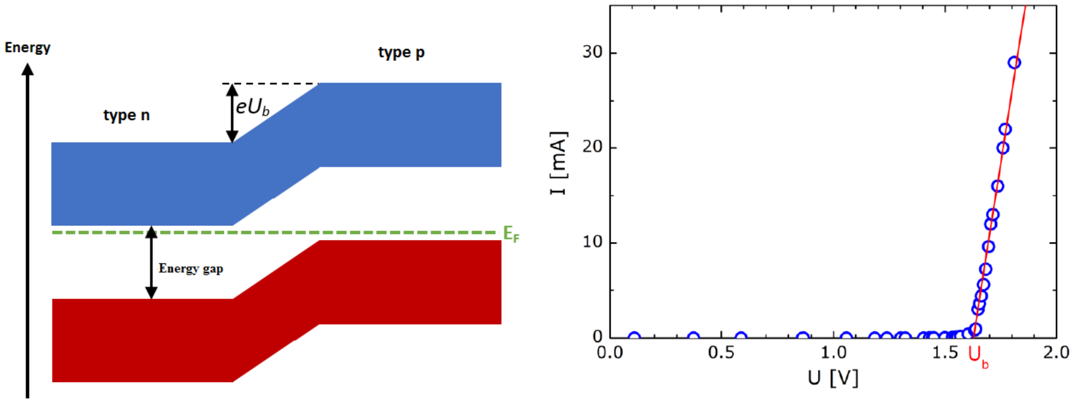


Fig. 8. (a) Band diagram of a p-n junction under forward bias polarization, (b) I-V characteristic of a diode measured applying the voltage in the forward direction. U_b – is a voltage referring to the potential barrier of a diode.