



11th EUROPEAN UNION SCIENCE OLYMPIAD

Test 1

Task sheet

Luxembourg, March 19th, 2013

Silicon
from
Nature
to
Hitech

Country:

Language:

General instructions

Wear a laboratory coat and safety glasses at all times within the laboratory.

Eating and drinking is prohibited in the laboratory.

Disposable gloves are provided and must be worn when handling chemicals.

All paper used, including rough work paper, must be handed in at the end of the experiment.

All results must be entered onto your final Answer sheet.

Your calculations must be handed in along with the Answer sheet.

Only the final answer sheet (first page in colour), and attached sheets, will be marked.

The tasks may be carried out in whatever order you wish.

The experiment consists of 3 Tasks and can be completed either individually or as a team.

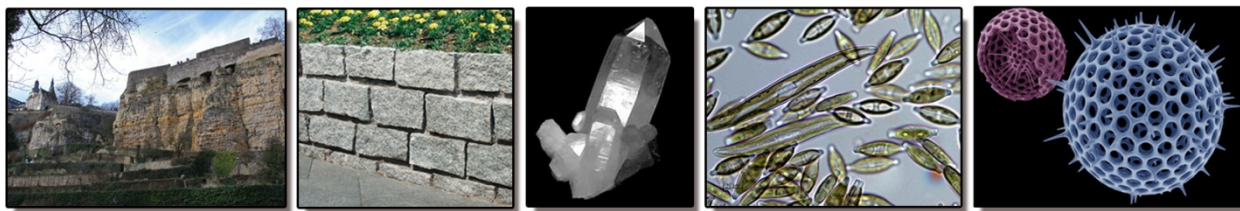
You have **3,5 hours** of time to complete Test 1

Task 1: 30 credit points

Task 2: 29 credit points

Task 3: 33 credit points

When you finish your tasks, leave everything on the desk. You are not allowed to take anything from the laboratory.



A silicon story

Silicon (Silicium), with the symbol **Si** is the eighth most common element in the universe. Over 90% of the Earth's crust is composed of silicate minerals in various forms of silicon dioxide (SiO_2). The most renowned form is **Quartz**. It can be found on beaches all over the world or as quartz sand or quartz crystals in sandstone, as granit or found in many other rock types. For example, the hosting city of the 2013 EUSO, Luxembourg, is built on sandstone rock which contains a high percentage of Quartz.

When SiO_2 is cooled rapidly, it does not crystallize, but solidifies as glass. This process is traditionally used to make quartz-based soda-lime glass, window glass, boro-silicate glass or fiberglass.

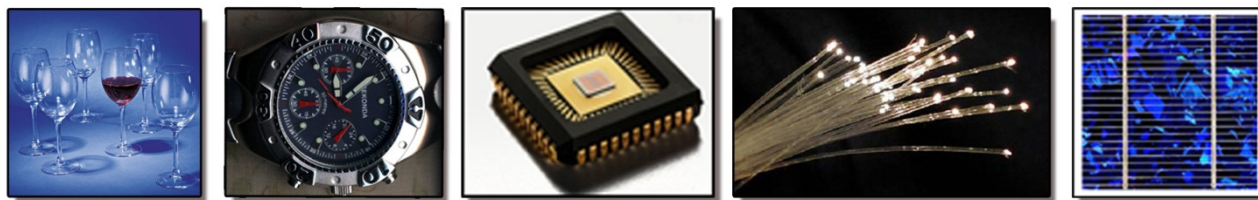
Today silicon has a large impact on modern technology. **Fibre optics**, used extensively in modern communication systems, relies on glass made of silicon. As a flexible optical fibre it functions as a waveguide, or optical pipe to transmit light over long distances between the two ends of the fibre. Wrapped in bundles these fibres are also used for illumination or fibre lasers.

Silicon is also an essential component in the computer industry, since the silicon **semiconductors** in each **micro-chip** are made from quartz. Rock Crystal has for a long time been used as an **oscillator** in watches and many other electronic products. Solar cell technology relies on Quartzite sand (SiO_2) to obtain pure crystal silicon which are then sliced and polished into the famous silicium wafers. These are key elements of **photovoltaic cells** in solar panels.

Silicon is also an essential element in Biology. Silicification in and by cells has been common in the biological world for well over a billion years. Silicon is an important **biomaterial** occurring in bacteria, single-celled organisms, plants, and animals. For example, microorganisms like Diatoms need silicon to build their microscopic protective cell wall. In nanotechnology, research on silicon devices as **nanovectors**, for targeted delivery of drugs, can provide essential breakthroughs in modern personalized medical care.

In the following test, teams of the 2013 EUSO, will solve different problems concerning silicon in nature and modern technology.

- **Task 1: Determination of SiO_2 in water**
- **Task 2: Diatoms, life in a silica box**
- **Task 3: SiO_2 in Solar Cell Technology**



TASK 1: DETERMINATION OF SiO₂ IN WATER

Background information

Silicon does not occur in its pristine state in nature, but rather as free silica (SiO₂) in coarsely crystalline (quartz, rock crystal, amethyst, etc) and microcrystalline (flint, chert, jasper, etc) varieties of quartz which is the major component of sand and sandstone.

Silicon therefore is usually reported as silica (SiO₂) when rocks, sediments, soils, and water are analyzed. The average abundance of silica in different rock types is 7 to 80% and in typical soils 50 to 80%. Typical concentrations in surface and groundwater lie between 10 and 20 mg/L.

Silica and phosphate react at pH 1.3 with ammonium molybdate to generate heteropoly acids. In order to isolate the molybdosilicic acid, tartaric acid is added to the solution destroying the molybdophosphoric acid. Boric acid is added to the solution to avoid fluoride interferences. The molybdosilicic acid complex slightly colours the solution light yellow. Over time the colour intensity is not stable and hence not suitable. Therefore, in order to obtain a more intense colour, the molybdosilicic acid is reduced by means of ascorbic acid to yield a blue colour. This additional step provides an increased sensitivity to the method and will allow for a more accurate determination of SiO₂ concentrations in tap and mineral waters.

The colour generated, in this manipulation, is proportional to the SiO₂ concentration present in the solution and can be measured using a spectrophotometer equipped with a filter at 800 nm. The measurement is made possible because the components of the solutions absorb part of the light which is directed at them. The degree of absorption is a function of the wavelength of the light radiation and the concentration in question.

In a given range of concentrations, there is a linear relationship between the absorbance of the sample and the concentration. This relationship is established using Lambert-Beer's law:

$$A = \epsilon \cdot l \cdot c$$

Where A is the absorbance measured by the spectrophotometer, ϵ is the molar absorption coefficient of the coloured substance, l is the distance that light beam has to travel (the absorption path length, which is simply the thickness or width of the cuvette) and c is the molar concentration. This means that for a given cuvette and for a given analyte;

$$A = K \cdot c \quad \text{or} \quad A = K' \cdot \gamma, \text{ where } \gamma \text{ is the mass concentration (mg/L)}$$

Where K is a constant.

A spectrophotometer is fundamentally a device that emits light, through the use of a lamp, at a controlled wavelength. This light travels across a given space in which a cuvette or tube is introduced. The cuvette contains the solution that which absorbance is measured. Part of the light passing through the solution is absorbed, and the loss of light is detected by a detector placed on the opposite side of the cuvette.

Equipment and material

- Marker pen, graph paper, stop watch
- Micropipette 100 μ l variable
- Micropipette 1000 μ L adjustable
- Pipette tips (blue and yellow)
- 3 Pipettes 5 mL plastic and pipetor
- Eppendorf 2 mL
- Support for Eppendorf vials
- Plastic vials 15 mL (Falcon)
- Cuvette (plastic, macro) for spectrophotometer
- Distilled water
- Silicium solution for calibration (1000 mg/L Si) labeled Si
- Boric acid (4 g in 100 mL) labeled “Boric Acid”
- Ammonium Molybdate (5 g in 100 mL H_2O) labeled “Molybdate”
- Tartaric acid (20 g in 100 mL) labeled “Tartaric Acid”
- Ascorbic acid (5 g in 100 mL) labeled “Ascorbic Acid”
- Sulfuric acid (5 g (1,84 g/mL) in 100 mL) labeled “Sulfuric Acid”
- 3 prepared solutions containing an unknown SiO_2 concentration labeled “Unknown 1”, “Unknown 2” and “Unknown 3”


On the main desk of the laboratory:

- Spectrophotometer with filter position at 800 nm

Description of the task

To determine the concentration of SiO_2 in three unknown samples, it is necessary to first measure the absorbance data corresponding to known concentrations of standard solutions. To measure the corresponding absorbance and deduce a calibration curve the solutions have to be prepared by performing a dilution from a silicium stock solution containing (1000 mg/L Si). The concentration of the unknown samples can be determined from the calibration curve.

TASK 1.1: Preparing the calibration solutions (8 marks)

- Calculate the SiO_2 concentration in mg/L of the given stock solution.  Answer sheet
- From the provided stock solution, prepare 10 mL of a 50 fold dilution. Calculate the volume of silicium stock solution needed for this dilution and note it on the Answer sheet. In order to avoid using a glass flask, you will have to work with plastic pipettes. Pipette 10 mL of distilled water into a 15 mL Falcon vial. From this 10 mL remove the volume previously calculated with a suited micropipette and discard this volume of distilled water and replace it with the silicium stock solution provided. Mark this solution as standard solution B.
- Prepare the calibration solutions from solution B. First label the 2 mL plastic vials from 1 to 6. Vial 1 (blank) will only contain the adequate proportions of distilled water and the reagents and will serve to adjust the spectrophotometer to zero absorbance.

Using the micropipette and suitable tips, prepare each vial with the quantities of water and solution B according to Table 1.1

Calculate the concentrations of the different solutions ☞ Answer sheet.

- d. Label the 15 mL plastic vials from 1 to 9. Vials 7, 8 and 9 will be used for the unknowns:

In each vial add the following in the indicated order:

- 0.5 mL of calibration solution or unknown using a micropipette
- 5 mL boric acid solution using a pipette
- 5 ml water using a pipette
- 1.2 mL sulfuric acid solution using a micropipette
- 0.4mL molybdate solution using a micropipette

Cover each vial, thoroughly mix the solution and wait 5 minutes

- e. Add to each vial 0.4 mL tartaric acid solution using a micropipette. Cover each vial, thoroughly mix the solution and wait 5 minutes
- f. Add to each vial 0.4 mL ascorbic acid solution using a micropipette. Cover each vial, thoroughly mix the solution and wait 5 minutes

	Solution B (mL)	Water (mL)
1	0	2
2	0.1	1.9
3	0.2	1.8
4	0.4	1.6
5	0.8	1.2
6	1.6	0.4

Table 1.1 : Calibration solutions

TASK 1.2: Establishing the calibration curve (16 marks):

Once the time has elapsed label the plastic cuvettes from 1 to 9. Do not mark on the translucent part on the cuvette, only on the opaque part of the cuvette!

Transfer the solutions 1 to 9 into the plastic cuvettes (filling at least $\frac{3}{4}$ of the total capacity of the cuvette).

- g. Check that the spectrophotometer is working (the spectrophotometer will be configured in advance by the laboratory supervisor)
- h. Insert cuvette 1 into the spectrophotometer in such a way that you can see the transparent side and the light ray will travel through the solution.
- i. Press the “Zero” key and the apparatus screen will show 0.000
- j. One by one insert each cuvette into the spectrophotometer and perform an absorbance reading by pressing the “Result” key. ☞ Answer sheet
- k. On a sheet of millimeter graph paper, draw a graph that represents the absorbance values of each silicate solution vs the concentration.
- l. Calculate the slope of the obtained curve ☞ Answer sheet
- m. Determine the concentrations of the 3 unknown samples, that were provided for this exercise, graphically and by calculation. ☞ Answer sheet

Once the experiment has finished, the contents of each vial and the liquid residues from washing each cuvette must be poured into the waste container provided.

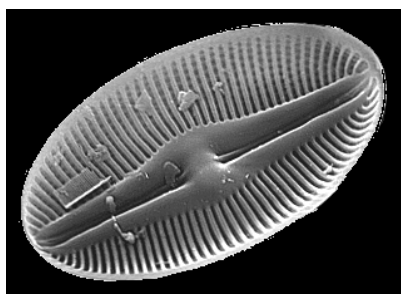
TASK 1.3: Error estimation (6 marks)

☞ Answer sheet

TASK 2: DIATOMS, LIFE IN A SILICA BOX

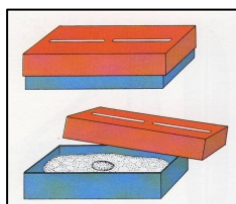
Background information about diatoms

Diatoms are microscopic unicellular photosynthetic **algae** found in freshwater, marine or terrestrial environments. Diatoms are frequently present as a brown slippery coating on submerged stones in rivers.



These organisms build a hard and porous cell wall called a **frustule**, a box-like structure composed almost purely of amorphous silica and various organic compounds. Diatoms are able to synthesize this biogenic silica cell wall intracellularly, at low temperatures by the polymerisation of silicic acid ($\text{Si}(\text{OH})_4$) monomers dissolved in the water they thrive.

The frustule is usually composed of two overlapping valves, fitting together like the two halves of a box. The valves have many pores and slits that allow the exchange of materials with the external environment.



Diatoms not only live in fresh water but can also be found in sea water. Estimated to contribute up to 45% of the total oceanic primary production, they are the most common type of **phytoplankton**. In the ocean alone diatoms are responsible for the binding of about 25% of carbon dioxide (CO_2) and thus giving off a large amount of the oxygen that people breathe.

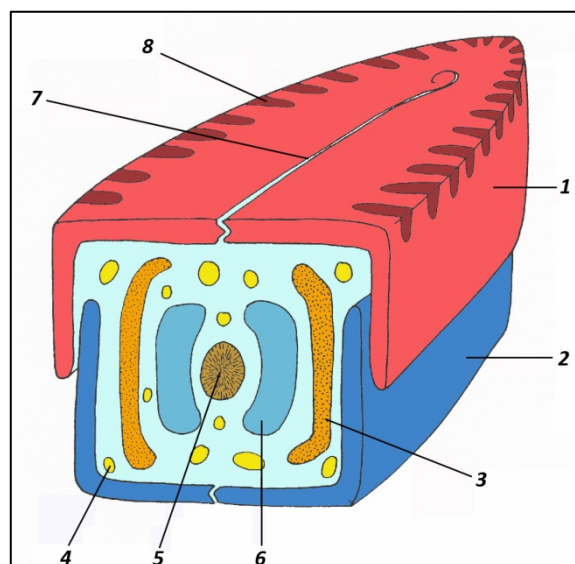


Fig. 2.1: Anatomy of a diatom: (1) upper valve of the frustule (epitheca), (2) lower valve (hypotheca), (3) brown coloured plastids with fucoxanthin, (4) oil droplets, (5) nucleus, (6) vacuole, (7) slit or raphe, (8) striae.



When diatoms die the frustules or valves are left behind. Diatomaceous earth, also known as **diatomite** (or **Kieselgur**) is a soft siliceous sedimentary rock that is formed from fossilized diatom frustules. It may be easily crumbled into a fine white powder with very high porosity and absorbent qualities, thus enabling various applications in modern industry. Fossil evidence suggests that diatomaceous earth originated during, or before the early Jurassic Period (-200 MA).

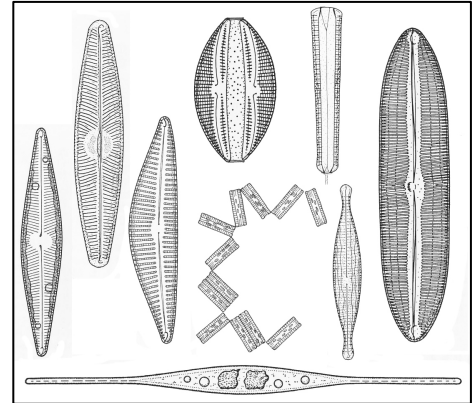
Diatom communities are a popular tool for monitoring environmental conditions, past and present, and are commonly used by scientists as bioindicators in studies of water quality.

Description of the task

In nature many thousands of diatom species are distinguished by the very variable architecture of this silicon box. Most diatoms are unicellular, although they can exist as colonies.

Task 2.1 Identification of diatom species

Each team will be provided with two microscopic slides with diatom frustules from the rivers *Syre* and *Gander* from Luxembourg. The diatoms have been prepared for you, so that you have two microscope slides with only the valves (or frustules) present. For identification of the diatoms you will need a microscope with a lens that magnifies up to 1000 times. Start your observation with a 10x and then 40x lens. For final magnification of 1000 times, you have to use the oil immersion technique. You will need to place a drop of immersion oil between the sample and the lens of the microscope.

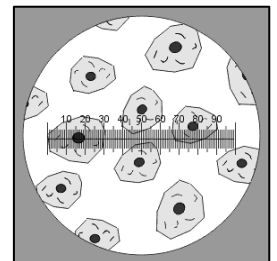


Joker: If you do not know how to perform the oil immersion technique, ask the laboratory assistant for a Joker. This will nevertheless cost you 3 marks!

As there are hundreds of different species occurring in Luxembourg, a simplified photographic determination key has been provided, especially for EUSO participants (see Appendix). In order to distinguish the different species, you will have to look at the **dimensions of the frustules** the **presence of a raphe** (see Figure 2.1) and distinguish **differences in surface structure** of the **valves** (including presence of striae, pattern and density).

The challenge of this task will be to observe with precision the valves present and sort the differences between the species.

The length may be determined using an ocular micrometer installed in one of the oculars on your microscope. A typical scale consists of 100 small divisions (units). You may turn the ocular with the micrometer in order to fit with the orientation of the diatom frustules.



The scale on the micrometer has been calibrated using a stage micrometer to indicate the length of each unit at a given microscope magnification. The scale is provided to you on the laboratory bench. The number of ocular units is multiplied by the calibration to determine the exact dimension of a measurement. (See also appendix 2)

Identify the following species looking at both samples using the attached photographic identification key and measure the mean length of each. You need to measure a minimum of 5 valves and check both slides. ☞ see Answer sheet.

Navicula cryptotenella (NCTE*)

Amphora pediculus (APED)

Mayamaea permitis (MPMI)

Nitzschia dissipata (NDIS)

(*) code of species name

Task 2.2 Determination of the water quality of two rivers from Luxembourg

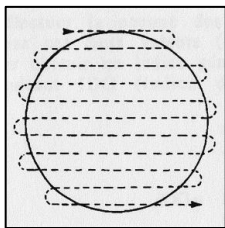
Diatoms are very sensitive to environmental change and thus may be used as indicators for water pollution. The riffle of a stream is sampled by brushing off diatoms from stones. From the diatom taxa list (Table 1), a pollution indicator score can be calculated.

The index currently in use all over Europe is the Specific Polluosensitivity Index (IPS). This index is based on the sensitivity of different diatom taxa to eutrophication and organic pollution and on the use of all diatom taxa found at a site.

To calculate the IPS, we take into account the ecological tolerance range (V) of each taxa in the sample (scored from 1 to 3, with 3 being taxa with a narrow tolerance range), the sensitivity to pollution (S) of each diatom species (scored from 1 to 5, with 5 being the most sensitive species) and the abundance (A), number of valves of each species, present in the sample (see Table 1 at the end of the document).

The abundance is determined by counting the different species present in each sample. The ecological tolerance and sensitivity for each species is given in Table 1.

Scientists, from the Public Research Center - Gabriel Lippmann in Luxembourg, have taken the samples of water and it is up to you now to examine each under a microscope to see how many of the different species of diatoms are present.



First you should identify the different species present with a magnification of 1000x. You should then count the number of frustules of each species (abundance A) and write it down on the answer sheet. In order to avoid double counting, you should choose an interesting area of the sample, and do the counting as shown in the given figure. It is suggested to first count the very small species! To get a statistically reliable IPS index, you have to consider at least 200 individuals on each sample slide.

With this data the index (IPS) can be calculated and scored from 1- 5 using the formula:

$$\text{IPS (on 5)} = \frac{\sum S \times V \times A}{\sum V \times A}$$

The IPS (on 5) is rescaled to have a **final IPS** score value between 1 (bad ecological quality) to 20 (high ecological quality). It is easily obtained using the following transformation formula:

$$\text{IPS (on 20)} = (\text{IPS (on 5)} \times 4.75) - 3.75$$

You may now determine the degree of water biological quality of the two rivers (*Syre* and *Gander*) using the following tolerance table: ☞ see Answer sheet.

IPS	17≤IPS<20	13≤IPS<17	9≤IPS<13	5≤IPS<9	1≤IPS<5
Biological quality classes	A = very good	B = good	C = tolerable	D = bad	E= very bad

Question 2A: Diatoms & technology (1 marks)

Alfred Bernhard Nobel (1833- 1896) was a famous swedish chemist, engineer and inventor.

He used his fortune to posthumously institute the well known Nobel Prizes.

He used diatomaceous earth (fossilized remains of diatoms), a siliceous sedimentary rock for his most famous invention. Which of the following inventions made him famous and rich? ➡ see Answer sheet.

Table 1: Reference table for sensitivity to pollution (S) and ecological tolerance range (V) of the diatoms illustrated (see the identification key)

Diatom species	Code	S	V
<i>Achnantheidium saprophilum</i>	ADSA	3	1
<i>Amphora pediculus</i>	APED	4	1
<i>Caloneis lancettula</i>	CLCT	5	1
<i>Diatoma moniliformis</i>	DMON	4	2
<i>Diatoma vulgare</i>	DVUL	4	1
<i>Eolimna minima</i>	EOMI	2.2	1
<i>Eolimna subminuscula</i>	ESBM	2	1
<i>Gomphonema olivaceum</i>	GOLI	4.6	1
<i>Gomphonema parvulum</i>	GPAR	2	1
<i>Mayamaea permitis</i>	MPMI	2.3	1
<i>Navicula cryptotenella</i>	NCTE	4	1
<i>Navicula gregaria</i>	NGRE	3.4	1
<i>Navicula lanceolata</i>	NLAN	3.8	1
<i>Navicula tripunctata</i>	NTPT	4.4	2
<i>Nitzschia dissipata</i>	NDIS	4	3
<i>Nitzschia sociabilis</i>	NSOC	3	3
<i>Nitzschia soratensis</i>	NSTS	1	3
<i>Rhoicosphenia abbreviata</i>	RABB	4	1
<i>Ulnaria ulna</i>	UULN	3	1
Species not illustrated in the key	ZZZZ	0	0

TASK 3: SiO₂ IN SOLAR CELL TECHNOLOGY

Background information about solar cells

Photovoltaic cells or solar cells are the building blocks of **solar modules** used on rooftops (see Figure 3.1 below). They have a metallic-blue or black appearance with a typical area of 100 cm². The thin silvery lines visible at the surface (see Figure 3.2 below) represent the **contact grid**. The surface is coated with an **anti-reflection layer**. A glass layer is then used to protect the cells from the elements.



Figure 3.1: Rooftop solar module

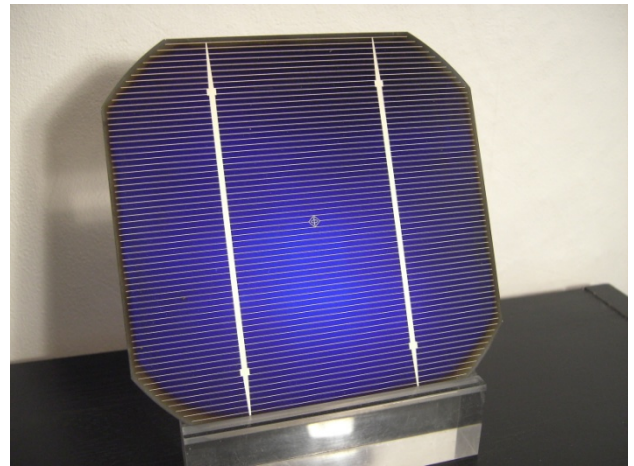


Figure 3.2: Solar cell with contact grid

When illuminated the solar cells convert light energy into electrical energy.

A solar cell is made of two layers of differently doped Silicon (Si) semi-conductors: in Figure 3.3 below, the upper layer is an **n-type** semi-conductor while the bottom layer consists of **p-type** semi-conducting material. Both types of semiconductors contain small amounts of characteristic impurity atoms (doping).

In an n-type semiconductor, each of the impurity atoms hosts one more electron than needed to integrate into the crystalline Si-lattice. These so-called excess electrons behave in the same way as the mobile electrons in a metal; they can also contribute to an electric current. While donating electrons, the impurity atoms become positive charged impurity ions.

In a p-type semiconductor, each of the impurity atoms hosts one less electron than needed to integrate into the crystalline Si-lattice. This vacancy, called hole, can be filled with an electron from a nearby Si-atom, thus creating a hole in the latter Si-atom, which in turn can be filled with an electron from another nearby Si-atom, etc. The result is that the holes are free to move and behave as positive mobile charges. Similar to the free electrons in the n-layer, they can also contribute to an electric current. While receiving electrons, the impurity atoms become negative charged impurity ions.

When the n-layer and the p-layer are brought into contact, electrons from the n-layer near to the **pn-junction** combine with holes from the p-layer. This process results in the formation of a so-called **depletion zone** (without any mobile charge carrier) with a characteristic charge distribution, formed by the impurity ions as illustrated in Figure 3.3. This charge distribution creates an electric potential difference (voltage) across the depletion zone.

As suggested by Figure 3.3 the upper layer, the n-layer, of the solar cell is exposed to light. It is a very thin layer (0.5 to 1 μm) that allows as much light as possible to reach the depletion zone. Generally the bottom layer (p-layer) has a thickness ranging from 300 μm to 500 μm .

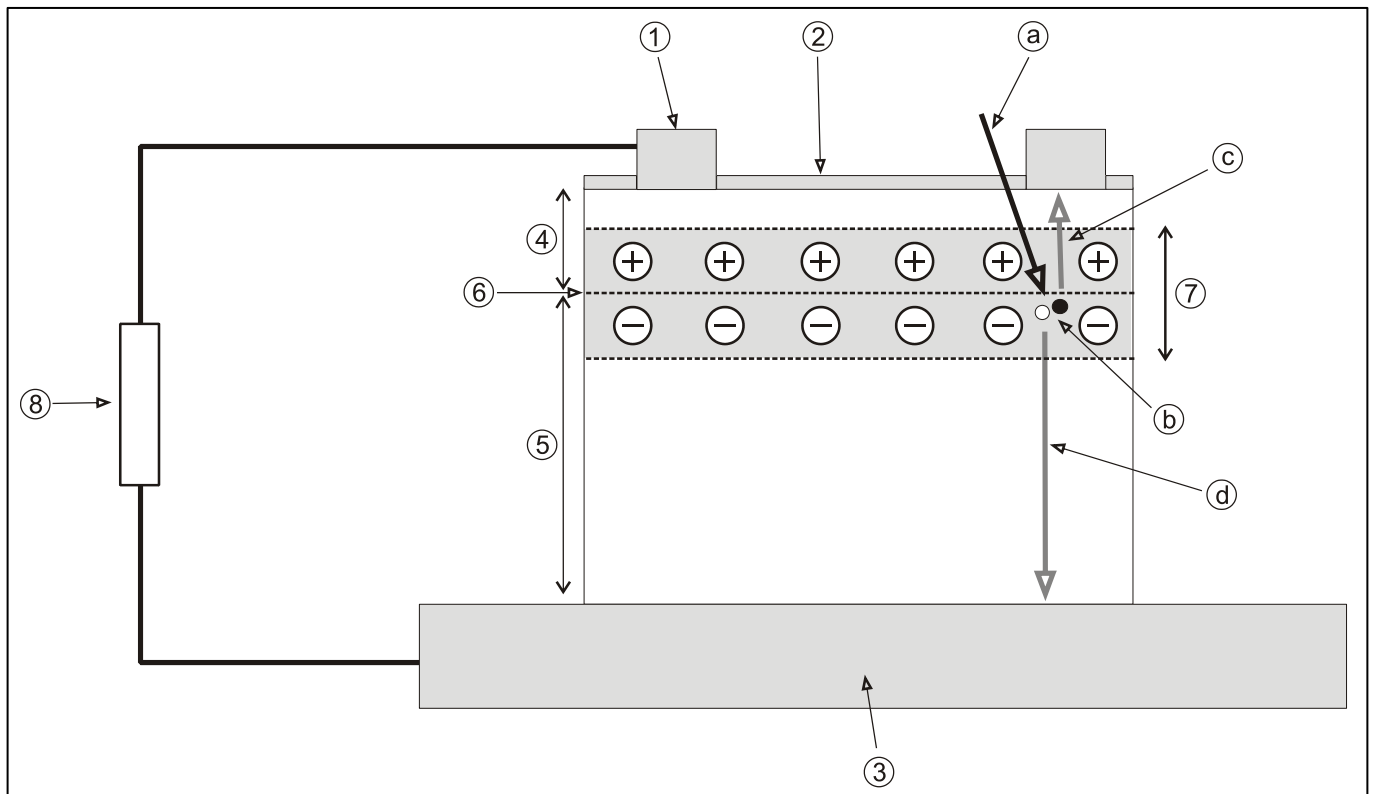


Figure 3.3: Structure of the solar cell: (1) contact grid, (2) anti-reflection coating, (3) base contact, (4) n-type semi-conductor, (5) p-type semi-conductor, (6) np-junction, (7) depletion zone, (8) external load resistor;

Functioning of the solar cell: (a) incident photon, (b) photon-induced creation of an electron-hole pair, (c) moving direction of the electron, (d) moving direction of the hole.

Light incident on the solar cell (= flux of photons) passes through the very thin n-zone to be subsequently absorbed in the depletion zone. The energy of **a single absorbed photon** can be used to create **one electron-hole pair** in the depletion zone and in addition heats up the solar cell. Such an event occurs with a certain probability described by the **quantum yield**. In a solar cell material with high quantum yield a large part of the incident photons create electron-hole pairs.

The voltage across the depletion zone drives the electron towards the top layer where it is collected by the contact grid and drives the hole to the base contact. If a load resistor R is connected to the cell as illustrated in Figure 3.3, the electron flows through the resistor back to the base contact where it recombines with the hole: an electrical current is flowing.

Question 3A

The **solar efficiency** η of a **solar module** is defined as $\eta = \frac{\text{electric power delivered}}{\text{incident light power}}$ (formula 1)

Which of the following factors will reduce the solar efficiency of a module illuminated by a huge number N of photons per second, each carrying enough energy to create an electron-hole pair?

- Reducing N
- Increasing the contact grid area
- Part of the incoming light being reflected
- Choosing a solar cell material with lower quantum yield
- Increasing the energy of the photons (assume a invariant quantum yield)
- Increasing the dirt on the glass layer
- Thicker layer of n-type semi-conductor
- Thicker layer of p-type semi-conductor
- Choosing a very high load resistance
- Choosing a very low load resistance

☞ Provide your answers on the answer sheet.

Description of the tasks

Your task consists of the following:

- measure the open circuit voltage U_{oc} across the illuminated cell and the short circuit current I_{sc} flowing through the cell,
- investigate the current – voltage and power – voltage characteristics of the cell,
- study series and parallel assemblies of two solar cells, and
- finally suggest how to assemble lots of cells in order to build a solar module with a given output power and voltage.

Equipment and Material

- Light source (halogen lamp 120W/230V)
- 2 solar cells
- 2 multimeters
- Wooden block
- Potentiometer box containing a series configuration of three potentiometers (100 Ω , 10 Ω and 5 Ω); its resistance can be varied from 0 to 115 Ω
- 7 connecting leads
- Ruler
- 2 sheets of millimetre paper

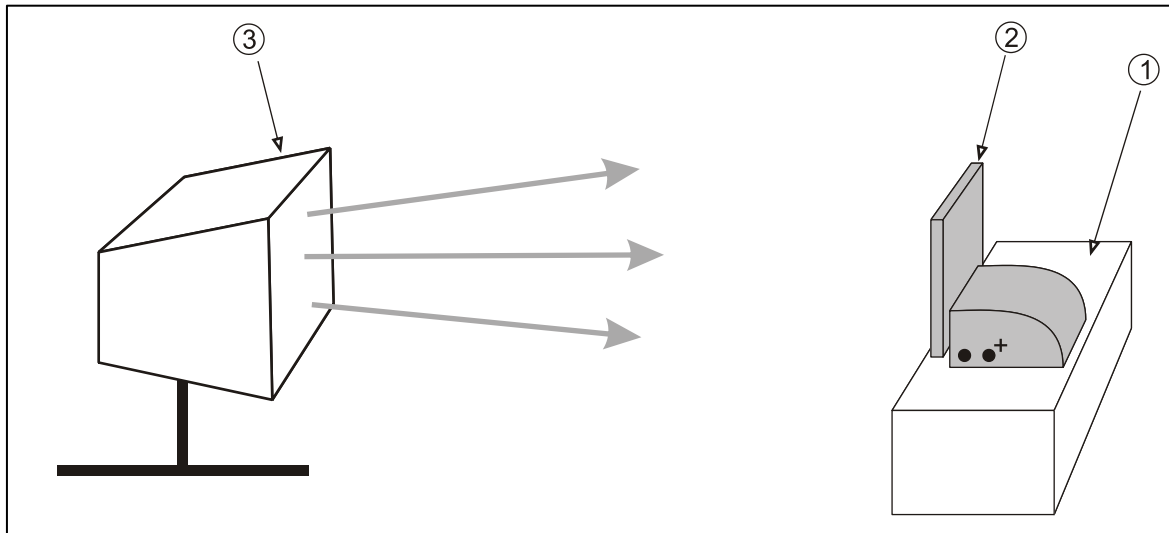


Figure 3.4: Experimental set up: (1) wooden block, (2) solar cell, (3) lamp

Set up the experiment as shown in Figure 3.4. The distance between the lamp and the cell should be kept at approximately 35 cm for Task 3.1 and 50cm for Task 3.3. The cell should be optimally illuminated.

Take care! The black casing of the lamp will get very hot.

Task 3.1: Open-circuit voltage U_{oc} and short circuit current intensity I_{sc} .

The distance between the lamp and the cell should be kept at approximately 35 cm.

To measure the open-circuit voltage across the illuminated cell, connect a multimeter as shown in Figure 3.5.

- First write the light source number and the cell number (located on the back) on the Answer sheet.
- Turn the rotary switch to the 2 V position (V=).
- Switch on the lamp and measure U_{oc} .
- Record the value on the Answer sheet.
- Leave the light switched on.

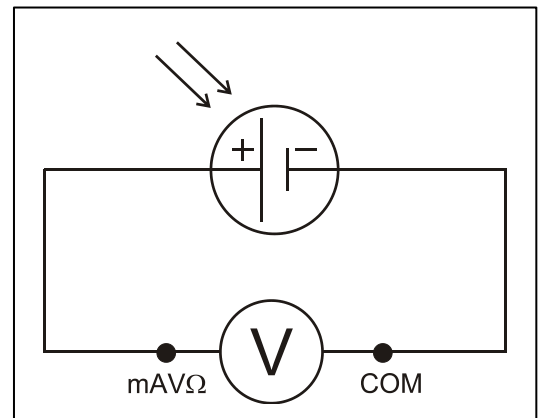


Figure 3.5: Open-circuit diagram

To measure the intensity of the short circuit current flowing through the illuminated cell connect a multimeter as shown in Figure 3.6. (Note: it is not a perfect short circuit since the load resistance is the small ammeter resistance.)

- Turn the rotary switch to the 200 mA position (A=).
- Measure I_{sc} .
- Record the value on the Answer sheet.

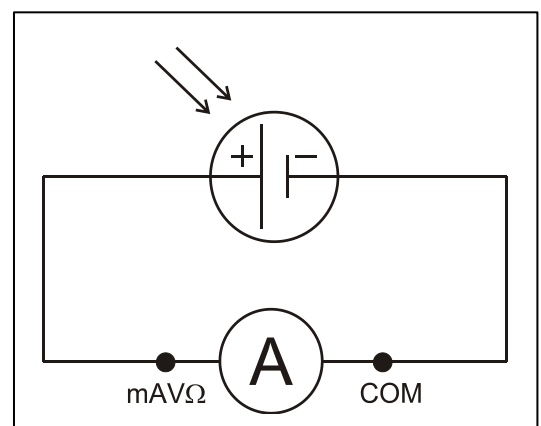


Figure 3.6: Short-circuit diagram

Task 3.2: Current – voltage and power – voltage characteristics

- Leave the solar cell in place (approximately **35 cm** from the lamp) and build the circuit shown in Figure 3.7. Use the potentiometer box as a load resistor.
- Vary the load resistance in order to change the intensity of the current flowing through the circuit. For this purpose **slowly turn** the knobs of the potentiometers.
- Measure the current intensity I and the voltage U across the cell for different load resistances.
- Record the values for I and U in the table provided on the Answer sheet.
- Draw the intensity dependence of the voltage as indicated in Figure 3.8.
- Calculate the electrical power $P = UI$, and record the values in your table on the Answer sheet.
- Represent the power P as a function of the voltage U in the same diagram (see Figure 3.8).

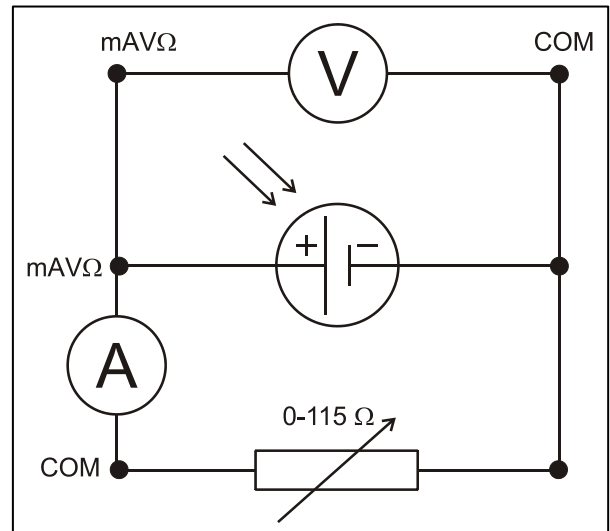


Figure 3.7: Circuit diagram with variable load resistor (potentiometer box) and multimeters

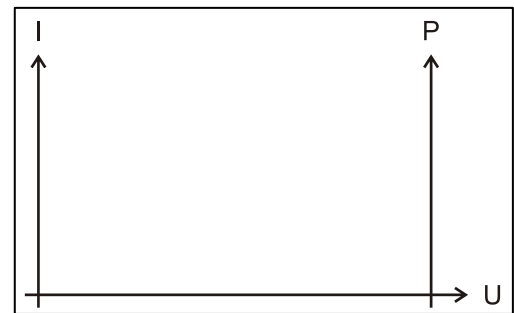


Figure 3.8: I/U/P diagram

When the solar cell operates at a voltage U_A and an intensity I_A , the corresponding point A on the $I-U$ graph is called the operating point (see Figure 3.9).

The rectangle determined by U_A and I_A is called **power rectangle**.

The area of the power rectangle associated to the operating point A, $U_A \cdot I_A$, is numerically equal to the power delivered by the cell at the point A.

A solar cell should operate at its **maximum power point** with coordinates (U_m, I_m) on the $I-U$ graph.

Identify the maximum power point on your graph and draw the corresponding power rectangle.

Record the values for U_m , I_m and P_m on the Answer sheet.

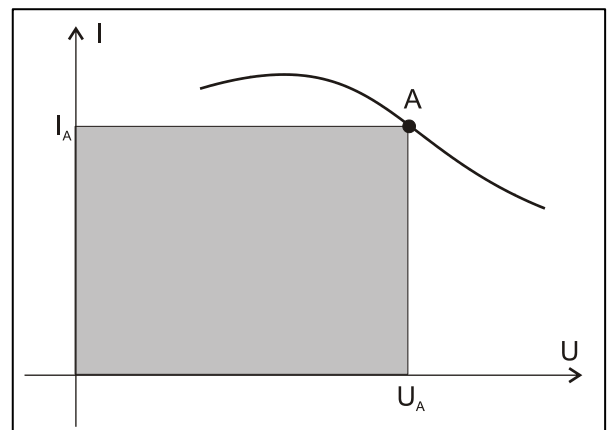


Figure 3.9: Power rectangle for operating point A

Question 3B

The efficiency of your solar cell (see formula 1) at the maximum power point is roughly equal to 8%. What is the incident light power per surface unit in your experiment?

☞ Provide your result on the Answer sheet.

Task 3.3: Combinations of solar cells

In a real solar module, cells are assembled in series and in parallel. The circuit you will study is still the one of Figure 3.7 with a single cell and with two cells combined, respectively.

Series combination (see Figure 3.10)

- Set up two solar cells in front of the lamp at a distance of approximately **50 cm** so that they are optimally illuminated.
- Measure the voltage across each individual cell for a same current intensity of 40 mA.
- Connect the two cells in series and measure the voltage across the unit for the same current intensity of 40 mA.
- Record the cell numbers and your values in the table of the Answer sheet.

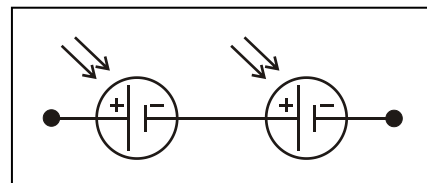


Figure 3.10: Series connection of solar cells

Parallel combination (see Figure 3.11)

- Keep the two solar cells in front of the lamp at a distance of approximately **50 cm**.
- Measure the current intensity through each individual cell for an output voltage of 0.40 V).
- Connect the two cells in parallel and measure the intensity of the current through the unit for the same output voltage of 0.40 V.
- Record the cell numbers and your values in the table of the Answer sheet.

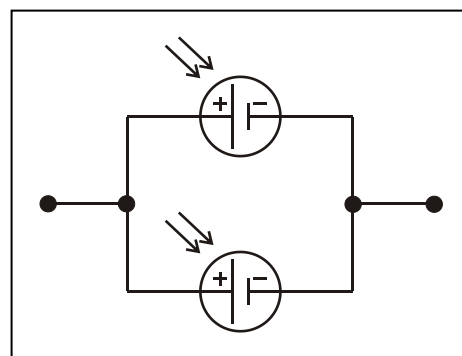


Figure 3.11: Parallel connection of solar cells

Question 3C

Consider a solar cell with a maximum power point defined by $U_m = 0.4 \text{ V}$ and $I_m = 0.125 \text{ A}$. Using a number of cells you should build a solar module delivering (at the maximum power point) an electrical power of 15 W at a voltage of 12 V.

To achieve this you have to combine the series and the parallel configurations.

- How many cells should you connect in series?
- How many of these series circuits should you connect in parallel?

☞ Provide your results on the Answer sheet.