Example of the examination Solar Cells (ET4-149)

Write your name on each piece of paper.

This examination consists of 7 tasks. Give short and concise answers to the tasks. Use the enclosed appendices A and B to carry out the calculations.

TASK 1: (20 points)
A 250-micrometer thick crystalline silicon wafer is doped with 5×10^{16} acceptors per cubic centimeter. A 1 micrometer thick emitter layer is formed at the surface of this wafer with a uniform concentration of 3×10^{19} donors per cubic centimeter. Assume that all doping atoms are ionized. The intrinsic carrier concentration in silicon at 300 K is $n_i = 1.5 \times 10^{10}$ cm^{-3}.

How large is (at 300 K and thermal equilibrium):

a) The electron and hole concentration in the p-type region and n-type region? Which charge carriers are the majority carriers in the p-type region and what is their concentration?
b) What is the position of the Fermi level (in eV) in respect to the conduction band in the p-type and n-type region, respectively?
c) The built-in voltage of the p-n junction?
d) Draw the corresponding band diagram of the p-n junction.
e) The width of the depletion region of the p-n junction. Compare it with the total thickness of the Si wafer.

TASK 2: (15 points)

a) Working of a solar cell is based on the photovoltaic effect. What is the photovoltaic effect and which are the fundamental processes behind this effect?
b) Demonstrate these processes using a schematic drawing of an amorphous silicon solar cell.
c) What is meant by *Energy pay back time* of a solar cell?

TASK 3: (20 points)

a) Explain the fundamental difference in the working between the crystalline silicon and the amorphous silicon solar cell.
b) Point out the differences between the solar cell structure of amorphous silicon and crystalline silicon. Draw the schematic structure of both single-junction amorphous and crystalline silicon solar cells.
c) Draw and compare the band diagrams for both the solar cells under thermal equilibrium.
d) Draw the I-V characteristic under dark and illuminated conditions for both the solar cells and point out the differences.

TASK 4: (10 points)

a) What are the external parameters of a solar cell and how are they determined?
b) How do the external parameters of a crystalline silicon solar cell depend on temperature?
c) Give typical values of external parameters of a commercial crystalline silicon solar cell. What is the efficiency of the best laboratory crystalline silicon solar cell?

TASK 5: (10 points)

a) Family Johan decide to place 4 solar modules (the description of the modules is given below) on their roof using a campaign of government energy department, in which they offer a complete solar cell system (including 4 modules) for the price of 950 €. How many years has to use family Johan the solar system to earn the costs of the system back? (The PV system is placed in The Netherlands where an average price of conventional electricity is 0.20 € per kWh. Solar insolation in the Netherlands is 1000kWh/m^2 per year.)

b) The total use of electricity in the Netherlands is at the moment 80 TWh per year. What should be the total area of solar cells that is needed to generate the present consumption of electricity in the Netherlands? (Use the same modules as family Johan)

Given:
The module efficiency is 15 % and the area is 1.5 m^2. The lifetime of the module is 25 years.

TASK 6: (10 points)

a) Name four major efficiency losses in a crystalline silicon solar cell? Explain them briefly
b) In the design of a crystalline silicon solar cell, which are the material parameters that determine the thickness of the solar cell.
c) Explain the approaches to make the solar cells more efficient by minimizing the optical losses.

TASK 7: (15 points)
Design a solar cell system for your summer house with 24V nominal operating voltage. The house appliances you have to use is given in the table:

DC appliances	***Power consumption [Watts]***	***Using Time /day in hours***
Refrigerator	150	5
Lamps	60	3
Television	60	3
AC appliances	***Power consumption [Watts]***	***Using Time /day in hours***
Washing machine	400	0.3
Microwave oven	800	0.5
Toaster	1100	0.25

The available solar cell modules, battery and inverter details are given below.

Solar insolation details		***The module properties***	
Hours of insolation/day	6 hours	Rated peak power	150W_P
		Rated peak voltage	34.0 V
		Rated peak current	4.4 Amp
Battery details		***Inverter details***	
Reserve time	4 days	Inverter system losses	15%
Usable battery power	80%		
Battery system losses	20%		

ANSWER 1 (20 points)
a) (4 points)

Hole concentration in the p-type region: $p = N_A = 5\times10^{16}\,cm^{-3}$

Electron concentration in the p-type region: $n = \frac{n_i^2}{N_A} = \frac{(1.5\times10^{10})^2}{5.0\times10^{16}} = 4500\,cm^{-3}$

Electron concentration in the n-type region: $n = N_D = 3.0\times10^{19}\,cm^{-3}$

Hole concentration in the n-type region: $p = \frac{n_i^2}{N_D} = \frac{(1.5\times10^{10})^2}{3.0\times10^{19}} = 7.5\,cm^{-3}$

The majority carriers in the p-type region are holes. The hole concentration is equal to the concentration of the (ionized) acceptor atoms N_A=5x10^{16} cm^{-3}.

b) (6 points)

Reference level E_C = 0 eV
In the n-type region:

$$n = N_C \exp\left(\frac{E_F - E_C}{kT}\right)$$

$$E_F - E_c = kT\ln\left(\frac{n}{N_C}\right) = 0.02586\times\ln\left(\frac{3.0\times10^{19}}{3.0\times10^{19}}\right) = 0.0\text{eV}$$

In the p-type region:

$$p = N_V \exp\left(\frac{E_V - E_F}{kT}\right) = N_V \exp\left(\frac{E_C - E_G - E_F}{kT}\right)$$

$$E_F - E_c = -kT\ln\left(\frac{p}{N_v}\right) - E_G = -0.02586\times\ln\left(\frac{5.0\times10^{16}}{1.0\times10^{19}}\right) - 1.10 = \text{-0.9629eV}$$

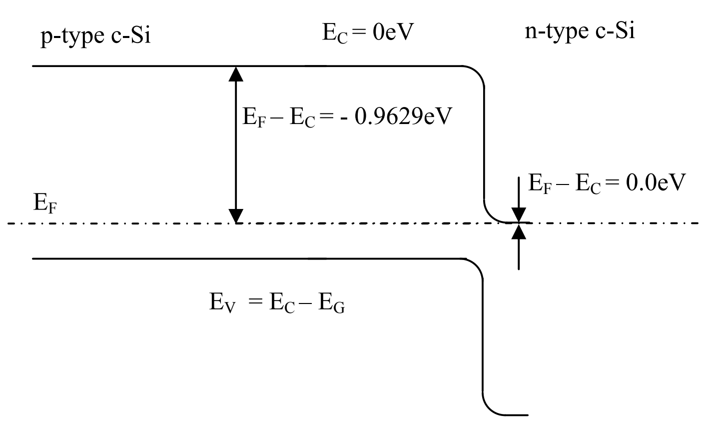


Figure. Band diagram for the crystalline silicon solar cell

c) (2 points)

The built-in voltage through the p-n junction is given by:

$$\psi_0 = \frac{kT}{q}\ln\left(\frac{N_A N_D}{n_i^2}\right) = 0.02586\times\ln\left(\frac{5.0\times10^{16}\times3.0\times10^{19}}{(1.5\times10^{10})^2}\right) = 0.942\ V$$

d) (6 points)
The band diagram is in the figure above.

e) (2 points)
The width of the depletion region is given by:

$$W = \sqrt{\frac{2\varepsilon_0\varepsilon_r}{q}\psi_0\left(\frac{1}{N_A}+\frac{1}{N_D}\right)} = \sqrt{12.94\times10^6\times0.942\times\left(2.0\times10^{-17}+3.33\times10^{-20}\right)} = 0.156\,\mu m$$

The width of the depletion region is (0.156 μm/250 μm) x 100% = ~0.063 % from the total thickness of the wafer.

ANSWER 2
a) (5 points)
The operation of today's solar cells is based on the ***photovoltaic effect*** in semiconductor materials. The photovoltaic effect means the generation of a potential difference at the junction of two different materials in response to visible or other radiation. The basic principles behind the photovoltaic effect in semiconductor materials are:

1. **Generation** of the electron-hole pairs due to the **absorption** of photons in the semiconductor materials that form a junction,
2. Subsequent **separation** of photo-generated electrons and holes in the junction,
3. **Collection** of the photo-generated carriers at the terminals of the junction.

b) (8 points)

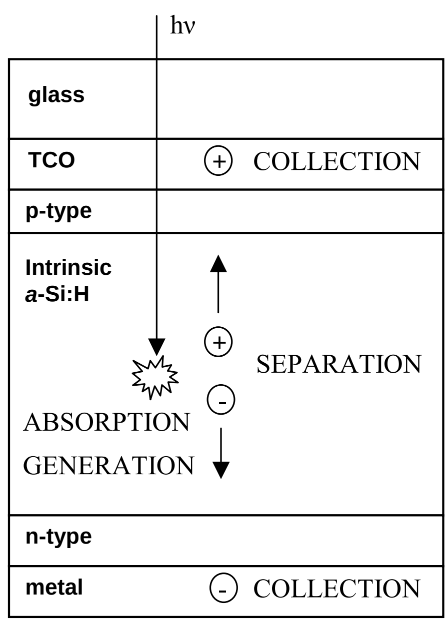


Figure. Schematic sketch of an amorphous silicon solar cell

d) (2 points)
Energy pay back time: the time required for an energy conversion system or device to produce as much energy as is consumed for its production

ANSWER 3.

a) (5 points)

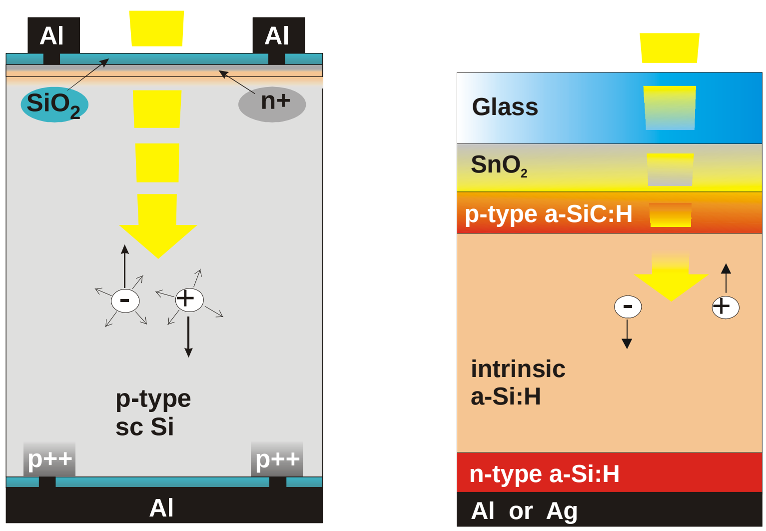
The differences between c-Si and a-Si solar cells:

a) The crystalline silicon solar cell is a diffusion-type device and the a-Si:H solar cell is a drift-type device.

b) (6 points)

a) For a c-Si solar cell the thickness is around 300 to 500 micrometer. The diffusion length of the minority carriers mainly affects the thickness of c-Si solar cell. For a-Si solar cell the thickness is around 300 to 400 nm. The thickness of a-Si:H solar cell is determined by the absorption coefficient and the degradation of a-Si material.

b) Structure of c-Si solar cell is p-n, where the structure of a-Si is p-i-n



A c-Si solar cell is a thicker cell, with the thickness around 300 to 500 micrometers. An a-Si is a thin film cell with the thickness around 300 to 400 nm. Structure of c-Si solar cell is p-n, where the structure of a-Si is p-i-n.

c) (4 points)

Band diagram (2+2 points) c-Si solar cell band diagram see figure in answer 1.

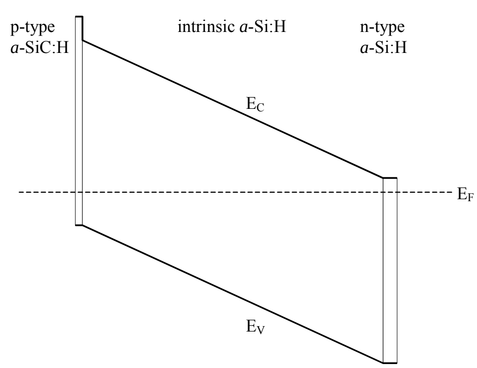
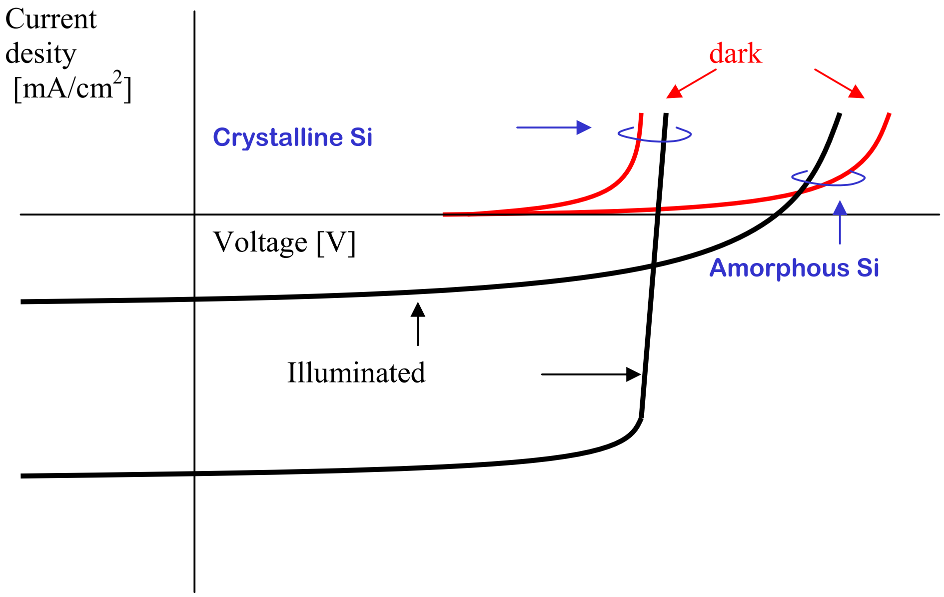


Figure. Band diagram for a-Si:H solar cell

d) IV characteristics (5 points)



In the amorphous silicon solar cell the dark and illuminated curves cross.

ANSWER 4.

a). (5 points)

External parameters: short circuit current, open circuit voltage; fill factor, efficiency, eventually series and parallel resistance. The external parameters are determined from I-V measurement, when the solar cell is illuminated. The standard illumination conditions are: AM1.5 spectrum, light intensity 1kW/m2, 25°C.

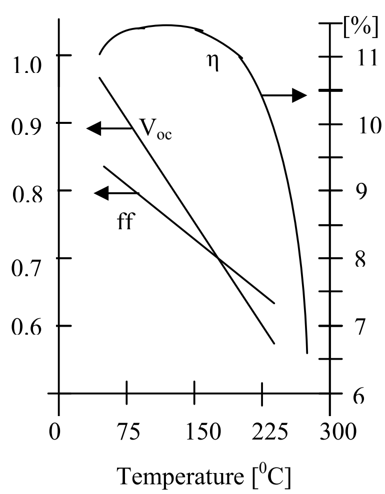
b) (3 points)

The total current is given by, $I_T = I_0(T)\left(e^{q(V+ITRS)/kT} - 1\right) - I_L$

Saturation current, $I_0 = KT^3 e^{-E_{g0}/kT}$

Open circuit voltage is, $V_{oc}(T) = \frac{E_{g0}}{q} - \frac{kT}{q}\ln\left(\frac{kT^3}{I_L}\right)$

The variation of fill factor, efficiency and open circuit voltage are given by the following graph



Both the fill factor and open circuit voltage has a linear relationship with temperature.

c) (2 points)
Typical values of the external parameters of c-Si and a-Si solar cells.:

	Open circuit voltage	Short circuit current	Fill factor	Efficiency
c-Si	0.6-0.7 V	30-40 mA/cm^2	0.8	18%
a-Si	0.75- 1 V	12-18 mA/cm^2	0.65-0.7	9%

Record efficiency of c-Si solar cell is 24.7%.

ANSWER 5.
Efficiency=15%, Lifetime 25 year, Solar insolation in The Nederland is 1000 kWh/m^2 per year.
a) (5 points)
1 module of 1.5 m^2 generates per year: 1000 kWh/ year * 0.15 * 1.5 = 225 kWh/ year.
4 modules generate: 4 x 225 kWh/year= 900 kWh/year.

The family spends 950 € for solar panels. So the electricity they can buy for this money from grid supply = 950/0.20 = 4750kWh
The number of years they have to use the panels to produce this much electricity = 4750 kWh/900 kWh/year = 5.3 years.

b) (5 points)
1 module of 1.5 m^2 generate 1000 kWh/year * 0.15 * 1.5 = 225 kWh/ year.

For 80 TWh/ year ($80 * 10^9$ kWh) the number of modules needed
$= 80 * 10^9/225 = 3.6 * 10^8$ modules.
Each module has an area of 1.5 m^2, so the area to be covered by modules = number of modules
$= 3.6 * 10^8 * 1.5\ m^2 = 5.4 * 10^8\ m^2 = 540\ km^2$

ANSWER 6:
a) (4 points)
The following are the major losses in a solar cell.

i) Loss by long wavelengths – Long wave length photons which have an energy less than the band gap energy of the semiconductor can not be absorbed.
ii) Loss by excess energy of photons – The energy equivalent to the band gap energy will be used to generate an electron hole pair. The excess energy possessed by the photon will be released to the crystal lattice and it will generate heat waves in side. In other words the semiconductor cannot use the excess energy possessed by a photon for carrier generation.
iii) Loss by metal electrode coverage by reflection and absorption –The metal electrode is used to collect generated electrons. This metal electrode covers the area over active layer and it reflects and absorbs the light falling on it. We make the electrodes in such a way that it exposes most of the area of active layer to sunlight. Still then there is a small portion covered by this electrode and we cannot use the light falling on this area.
iv) Loss by reflection from the active layers – All the materials other than a perfect black body reflect or transmit light at an interface. So at every interface of a solar cell there is a transmission and reflection of light. The reflection from the top most interfaces is a loss, as it cannot be used for carrier generation.
v) Loss by incomplete absorption due to finite thickness –All the photons in the light cannot be absorbed in a finite thickness. The will be getting transmitted through the back electrode
vi) Loss due to recombination – In the crystal lattice of a semiconductor there will be defects and impurities present. These defects and impurities can capture generated carriers and will act as recombination centers.

vii) Voltage factor – This is determined by the internal electric field acting in the p-n junction. If this field is lower we will have low open circuit voltage.
viii) Fill factor – The loss in fill factor is due to series and shunt resistance.

b) (3 points)
Absorption coefficient of each layer of the solar cell and diffusion length of the minority carries carriers
c) (3 points)
Texturing of the interfaces of the solar cell, use of highly reflecting back contacts, use of antireflection coatings.

ANSWER 7:

DC devices:

Refrigerator -	150 * 5	=	750Wh/day
Lamps -	60 * 3	=	180Wh/day
Television -	60 * 3	=	180Wh/day
DC power needed		=	750+180+180
		=	1110Wh/day

AC devices:

Wash. Mach.	400 * 0.3	=	120Wh/day
Micro. Oven	800 * 0.5	=	400Wh/day
Toaster	1100 * 0.25	=	275Wh/day
AC power needed		=	120+400+275
		=	795Wh/day
DC equivalent for AC		=	AC power/inverter efficiency
		=	795/0.85
		=	935.29Wh/day = 936 Wh/day
Total DC power per day		=	1110+936
		=	2046 Wh/day
System nominal dc voltage		=	24V
Amp-h/day needed		=	2046/24
		=	85.25 Ah/day
Battery losses		=	20%
Total Ah needed after considering the losses		=	85.25 * 1.2
		=	102.3 Ah/day
Average hours of sunshine per day		=	6 hours
Total PV array current		=	102.3/6
		=	17.05 Amp
Module operating current		=	4.4 Amp

Number of modules in parallel	=	17.05/4.4 = 3.875 → 4
System nominal voltage	=	24.0V
Module operating voltage	=	34.0V
Number of modules in series	=	24/34 = 0.705 → 1
Total modules required	=	modules in series * modules in parallel
	=	4 * 1
	=	4
Daily Ah requirement	=	102.3 Ah/day
Reserve days needed	=	4 days
Usable battery capacity	=	80%
Minimum battery capacity	=	102.3 * 4 /0.80
	=	511.5 Ah

So the design is:

1) 4 solar cell modules of peak voltage 34.0V and peak current 4.4Amp are to be connected in parallel
2) Inverter of efficiency 85% to be used
3) Battery capacity should be a minimum of 511.3Ah. Battery can be discharged up to 80% and charging losses are 20%.
4) System is designed for 24V operation
5) It has 4 days reserve time.