PHYS-E6570 Solar Energy Engineering (5 cr) **2nd mid-term exam** **5.4.2018**

Answer all five (5) questions.

1.

Explain briefly each concept (bolded) and answer the related questions (6 p)

a) **Nominal power rating of a photovoltaic module**, also called "watt-peak" or "peak-watt" (W_p). How does the power rating relate to the energy conversion efficiency of the module, and at which conditions is it determined?

b) **N- and P-type silicon.** What are the most common N- and P-type dopants in silicon? Why and how do affect the conductivity of silicon?

c) **Electron diffusion length**. How does it affect the solar cell performance and which two material semiconductor parameters determine it?

d) **Stand-alone photovoltaic system for a cottage.** Draw a schematic figure of the system and name its components in the case when both DC and AC electricity needs to be available for use at all times throughout the year.

e) **Multi-junction solar cell**. Why can they reach higher efficiency than single junction cells?

f) **Levelized cost of electricity (LCOE)**. When is residential solar electricity expected to become economically competitive to typical homeowners in Finland?

2.

Let's consider how doping affects the position of Fermi level in a semiconductor.

a) What is the energy difference between the Fermi level and the conduction band edge at $T = 300$ K, when the semiconductor, whose effective density of states in the conduction band is $N_C = 2.1 \cdot 10^{25}\,/\mathrm{m}^3$, is doped with donors atoms at density $N_D = 7.6 \cdot 10^{21}/\mathrm{m}^3$? (2 p)

b) What is the difference between the valence band edge and the Fermi level, if a semiconductor, whose effective density of states in valence band is $N_V = 1.6 \cdot 10^{25}/\mathrm{m}^3$, is doped with acceptor atoms at density $N_A = 2.2 \cdot 10^{22}/\mathrm{m}^3$? (2 p)
Boltzmann constant $k = 8.617 \times 10^{-5}$ eV·K^{-1}.

3.

Consider the theoretical and practical efficiency of a single-junction solar cell and module at standard reporting conditions (AM1.5G 1000 W/m^2, 25 °C).

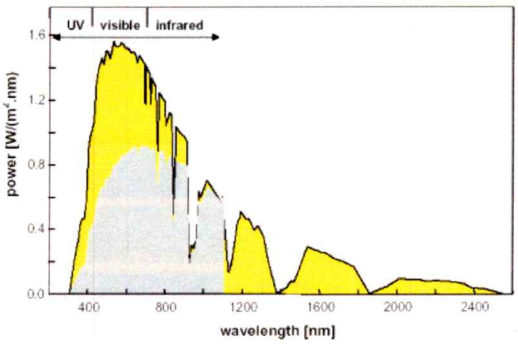
a) Which two fundamental loss mechanisms already together limit the theoretical efficiency to ca. 45 %?

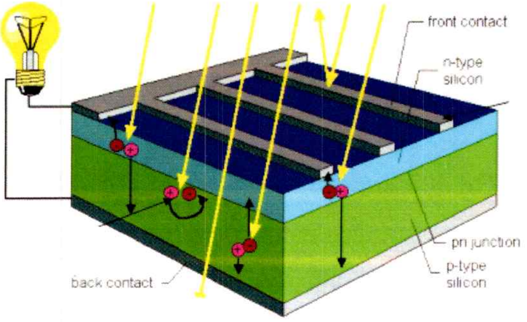
b) What additional fundamental physical process limits the theoretical efficiency to ca. 33 %?

c) What additional practical loss mechanisms limit the efficiency of real silicon solar cells to the current record of 27.6 %, and commercial silicon solar cells to 18 - 22 %?

d) What additional loss mechanisms are the reason why silicon solar modules have somewhat lower efficiency that the solar cells that they are built from?

Name and briefly explain these loss mechanisms and identify the key material properties that determine them. The figures below are given as a hint. (6 p)





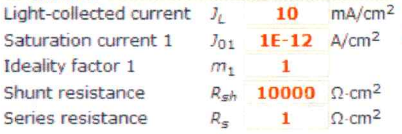
4.

The figures (ii)-(vi) below show current–voltage (IV) curves of solar cells measured at the standard test conditions (STC, radiation intensity 1000 W/m^2, AM1.5G spectrum, temperature 25°C). The IV curves can be represented with an equivalent circuit model which has five parameters: light-collected current J_L, saturation current density J_0, ideality factor m, shunt resistance R_{sh}, and series resistance R_s.

a) Draw the equivalent circuit corresponding to the IV curve and name its components. (1 p)
b) Using the five parameters, give the corresponding mathematical expression of the IV curve. (1 p)
c) Figure (ii) is the reference case, obtained with the parameter values of the table in figure (i). Estimate approximately from figure (ii) the open circuit voltage (V_{OC}), short circuit current density (I_{SC}), fill factor (FF), and energy conversion efficiency (η). (1 p)
d) Figures (iii)-(vi) represent each variation of one of the parameters: J_L, J_0, R_{sh}, and R_s vs. the reference value. Which figure corresponds to variation of which parameter? (1 p)
e) Estimate the range of variation (lowest and highest value) of the parameter values corresponding to the curves. (1 p)
f) Name which material or structural property could cause these variations in a solar cell. (1 p)

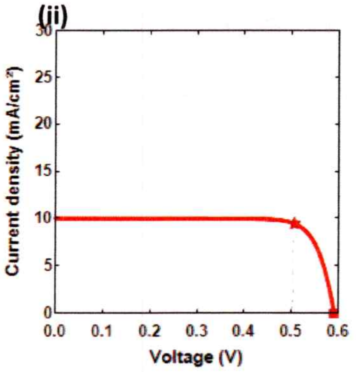
Boltzmann constant $k = 8.617 \times 10^{-5}$ eV·K^{-1}.

(i)

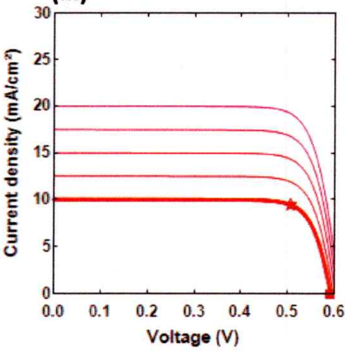


INPUTS			
Light-collected current	J_L	10	mA/cm^2
Saturation current 1	J_{01}	1E-12	A/cm^2
Ideality factor 1	m_1	1	
Shunt resistance	R_{sh}	10000	Ω·cm^2
Series resistance	R_s	1	Ω·cm^2

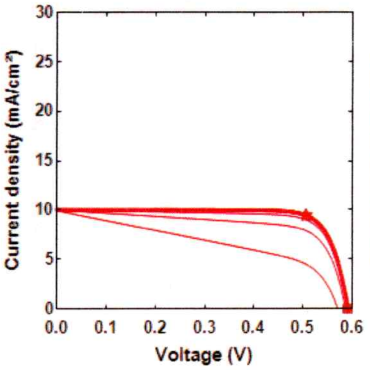
(ii)



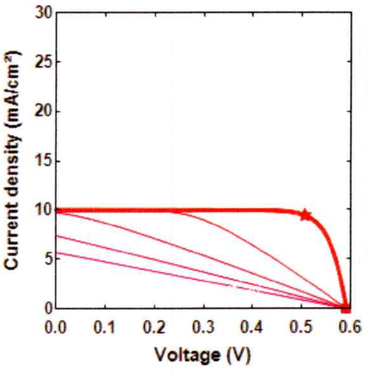
(iii)



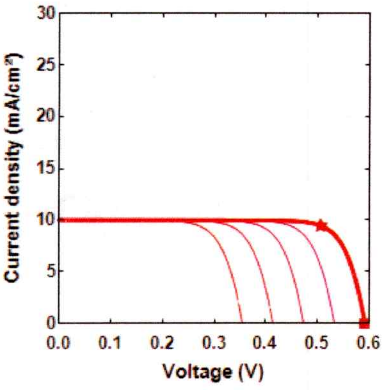
(iv)



(v)



(vi)



5.

Let's consider a grid-connected PV system installed on the roof of a single family house in Southern Finland, where the average total cost of grid electricity is 0.10 €/kWh. The yearly total solar irradiation on the module surface has been estimated to be 900 kWh/m^2 per year. The efficiency of the PV modules is 17 % and their expected operational lifetime is 25 years. The household consumes 7300 kWh electricity per year (120 m^2 floor area, four persons, no electric heating). Neglecting the time value of money, and assuming that the household can sell their surplus PV electricity at the same price as they electricity from the grid (net metering on a yearly basis),

a) How low should the investment costs (€/m^2 of module area) of the PV system be, to make the generated PV electricity competitive with the grid electricity? (1 p)
b) What are the investment costs of this system per rated power (€/W$_p$)? (1 p)
c) How large roof area must be covered with the PV modules to generate as much PV electricity as the household consumes per year? (1 p)
d) What is the investment cost of this system (€)? (1 p)
e) How does the time value of money affect the cost of PV electricity produced? (1 p)
f) What other factors should a more precise economic calculation take into account? (1 p)

PHYSICAL CONSTANTS

q	electronic charge	1.602×10^{-19} coulomb
m_0	electronic rest mass	9.108×10^{-31} kg
c	velocity of light in vacuum	2.998×10^{8} m/s
ε_0	permittivity of free space	8.854×10^{-12} farad/m
h	Planck's constant	6.625×10^{-34} joule × s
k	Boltzmann's constant	1.380×10^{-23} joule/K
kT/q	thermal voltage	0.02586 V (at 300 K)
λ_0	wavelength in vacuum associated with photon of 1 eV energy	1.239×10^{-6} m