@ exam. How many modules. area etc. Sth about cost.

Also small questions. General questions. pn junction thickness. crystalline silicon technology.

DC device	Device Watts	Hours of daily use	DC Watt-hrs. per day
computer	50	4	200
TV set	60	3	180
Light	160	4	640
Light - living 2.	40	8	320

Total DC Watt-hrs. per day 1340 (710 ← calc of others)

Rest, it keeps the temp.

AC device	Device Watts	Hours of daily use	AC Watt-hrs. per day
Fridge	350	0.5	175

Total AC Watt-hrs. per day 175

AC/0.85=DC Watt-hrs. per day 206

1. Total DC Watt-hrs./day (DC loads)		710
1. Total DC Watt-hrs./day (AC loads)	+	206
1. Total DC Watt-hrs./day (All loads)	=	916
System nominal DC voltage	÷	12
Total DC Ams-hrs./day	=	76
2. Battery + system losses	×	1.2
Total daily Ams-hrs. requirement	=	91.2 ≈ 92
3. Design insolation (ESH)	÷	2
4. Total PV array current (Amps)	=	46
Select module type		
5. Module operating current (Amps)	÷	8.8
Number of modules in parallel	=	5.2 → 6
System nominal volatge		12
Modules nominal voltage	÷	12
Number of modules in series	=	1
Number of modules in parallel	×	6
Total modules required	=	6
6. Total daily Amp-hrs. requirement		92.
Recommended reserve time (days)	×	3
Percent of usable battery capacity	÷	0.8
Minimum battery capacity	=	345

→ DC voltage of the system is chosen so.

92 A-h / day × 1 day / 2 hour = 46 A

→ 2 sun hours in winter time @ Italy.

From spec. of c-Si PV module
Config: 12/24 V
Related: 17/34 V volt
we don't need to increase voltage but the current. So we need to connect them in series.

Sample Examination of Solar Cells (ET4-149)

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: (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 schematically using a sketch of a solar cell (use a single junction amorphous silicon solar cell on glass as an example). figure 7.8

c) Draw the corresponding band diagram of an amorphous silicon solar cell. 7.9 fig.

Answers:

a) The photovoltaic effect means the generation of a potential difference at the junction of two different materials in response to visible or other radiation.

Fundamentally, the device needs to fulfil only two functions: photogeneration of charge carriers (electrons and holes) in a light-absorbing material, and separation of the charge carriers to a conductive contact that will transmit the electricity (simply put, carrying electrons off through a metal contact into a wire or other circuit).

b) Demonstrate these processes schematically using a sketch of a solar cell (use a single junction amorphous silicon solar cell on glass as an example).

c) Draw the corresponding band diagram of an amorphous silicon solar cell.

TASK 2: (20 points)

A 350-micrometer thick crystalline silicon wafer is doped with 1×10^{17} acceptors per cubic centimeter. An emitter layer of 1 micrometer is formed at the surface of this wafer with a uniform concentration of 5×10^{20} donors per cubic centimeter. Assume that all doping atoms are ionized. The intrinsic carrier concentration in silicon at 300 K is $n_i = 1.18 \times 10^{10}$ cm^{-3}.

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

a) The electron and hole concentration in the p-type and n-type region, respectively? 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? Draw the corresponding band diagram of the p-n junction.

c) the built-in voltage of the p-n junction?

d) the width of the depletion region of the p-n junction. Give your answer in micrometers and also as a percentage of the total thickness of the Si wafer. Which doped region forms the larger part of the depletion region?

TASK 3: (20 points)

a) Which are the external parameters that describe the performance of a solar cell and explain how these external parameters are measured and determined? Use a sketch to illustrate the determination of the external parameters.

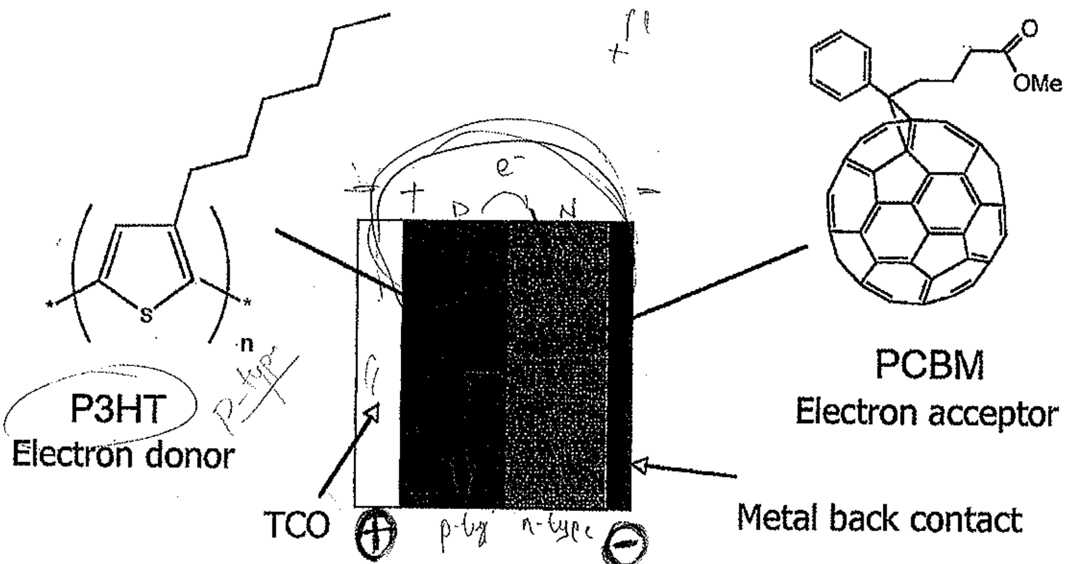
b) What are the main loss mechanisms in a solar cell?

c) Draw the schematic structure of a wafer-based c-Si solar cell. What is a typical thickness of a wafer-based c-Si solar cell? Describe which external parameters are mainly affected when the thickness of the solar cell is significantly decreased.

d) How can be the absorption in the solar cell increased without increasing its thickness? Describe at least two methods. Indicate how the external solar cell parameters are influenced when these methods are introduced.

TASK 4: (15 points)

The schematic structure of an organic solar cell is given below. The solar cell consists of a stack of two layers of organic materials sandwiched between a transparent conductive oxide (TCO) top contact and a metal back contact. The optical bandgap of the polymer P3HT is 1.8 eV and the optical bandgap of PCBM 2.3 eV.



a) Which contact will be positive and which negative under illumination? Which from two organic materials is considered to be p-type? Explain why?

b) Draw schematically the energy band diagram of the stack of organic materials in the solar cell. The driving force for charge separation at the junction of organic materials is 0.9 eV and the electron affinity for the electron acceptor material is 3.8 eV. What's the maximum possible open circuit voltage (equal to the effective band gap) of the organic stack for this solar cell?

c) Is a two-layer stack of organic materials good or bad geometrical configuration for a solar cell based on organic materials? Explain shortly why.

d) Calculate the minimum thickness of the P3HT layer in order to absorb 90 % of the incident light at 500 nm. The polymer has a value of extinction coefficient at 500 nm (imaginary part of the complex refractive index) k = 0.72. Neglect the reflection.

LABORATORY OF ELECTRONIC COMPONENTS, TECHNOLOGY AND MATERIALS

Examination Solar Cells (ET4149)
Tuesday August 26, 2008, 14.00 - 17.00

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: (10 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 a crystalline silicon solar cell.
c) What are the transport mechanisms of the charge carriers in crystalline silicon? Describe them shortly.
d) What is meant by the ***Energy pay back time*** of a solar cell?

TASK 2: (20 points)

A 250 micrometer thick crystalline silicon wafer is doped with 2×10^{16} acceptors per cubic centimeter. A 1 micrometer thick emitter layer is formed at the surface of this wafer with a uniform concentration of 1×10^{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):

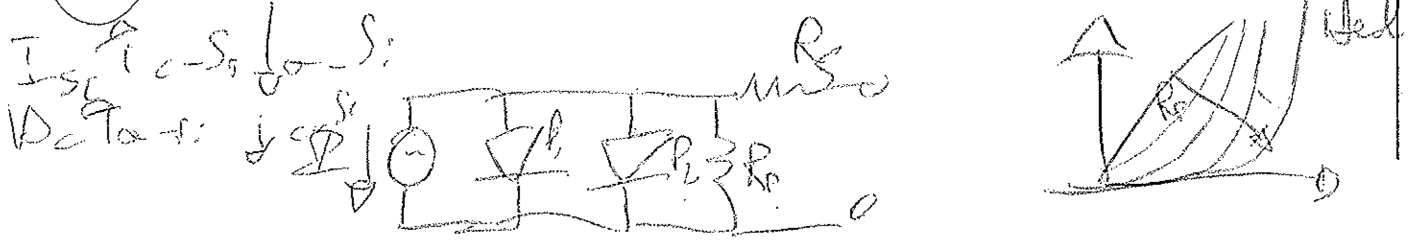
a) The electron and hole concentrations in the p-type region and n-type region, respectively? Which charge carriers are the majority carriers in the n-type region?
b) What is the position of the Fermi level (in eV) **in respect to the conduction band** in the p-type and n-type regions, respectively?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

TASK 3: (15 points)

a) Draw a schematic structure of a superstrate single-junction amorphous silicon solar cell. Describe the function of the individual layers that form a single-junction amorphous silicon solar cell in the superstrate configuration.
b) Explain the fundamental difference in the structure and the working between the crystalline silicon and the amorphous silicon solar cells.
c) Which deposition technique is widely used for fabrication of amorphous silicon and what are their advantages and drawbacks?

TASK 4: (15 points)

a) What are the external parameters of a solar cell and how are they measured and determined? Use a sketch to illustrate the measurement and determination of the external parameters.
b) Sketch an equivalent circuit of a solar cell with a series and parallel resistances.
c) How do the external parameters of a solar cell depend on a series and parallel resistances? Draw an illuminated I-V characteristic to demonstrate the effects.
d) Give typical values of external parameters of a crystalline silicon solar cell and amorphous silicon solar cell.



VAKGROEP ELEKTRONISCHE COMPONENTEN, TECHNOLOGIE EN MATERIALEN

Examination Solar Cells (ET4-149)

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: (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 schematically using a sketch of a solar cell (use a single junction amorphous silicon solar cell on glass as an example).
c) Draw the corresponding band diagram of an amorphous silicon solar cell.

TASK 2: (20 points)

A 350-micrometer thick crystalline silicon wafer is doped with 1×10^{17} acceptors per cubic centimeter. An emitter layer of 1 micrometer is formed at the surface of this wafer with a uniform concentration of 5×10^{20} donors per cubic centimeter. Assume that all doping atoms are ionized. The intrinsic carrier concentration in silicon at 300 K is $n_i = 1.18 \times 10^{10}$ cm^{-3}.

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

a) The electron and hole concentration in the p-type and n-type region, respectively? 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? Draw the corresponding band diagram of the p-n junction.
c) the built-in voltage of the p-n junction?
d) the width of the depletion region of the p-n junction. Give your answer in micrometers and also as a percentage of the total thickness of the Si wafer. Which doped region forms the larger part of the depletion region?

TASK 3: (10 points)

a) Draw a schematic structure of an amorphous silicon (a-Si:H) single junction solar cell. Sketch the IV characteristics of a typical a-Si:H solar cell at the standard illumination and discuss the external parameters of the cell.
b) The measurements of the illuminated IV characteristics of an a-Si:H solar cell show that the fill factor of the cell is low. Give at least 2 possible reasons for the low fill factor.
c) One of the problems in a-Si:H solar cells that lowers the performance of the cell is the high series resistance. Explain what the cause of the series resistance can be and point out two places in the a-Si:H solar cell where the problem of a high series resistance can occur.

TASK 4: (20 points)

a) Explain the fundamental difference in the working between a crystalline silicon and an amorphous silicon solar cell.

TASK 3: (10 points)

a) Draw a schematic structure of an amorphous silicon (a-Si:H) single junction solar cell. Sketch the IV characteristics of a typical a-Si:H solar cell at the standard illumination and discuss the external parameters of the cell.

b) The measurements of the illuminated IV characteristics of an a-Si:H solar cell show that the fill factor of the cell is low. Give at least 2 possible reasons for the low fill factor.

c) One of the problems in a-Si:H solar cells that lowers the performance of the cell is the high series resistance. Explain what the cause of the series resistance can be and point out two places in the a-Si:H solar cell where the problem of a high series resistance can occur.

TASK 4: (20 points)

a) Explain the fundamental difference in the working between a crystalline silicon and an amorphous silicon solar cell.

b) Draw the band diagrams for both types of solar cells. Sketch the IV characteristics in dark and under standard illumination for both types of solar cells. How can you determine from the IV characteristics, which type of solar cell you measure?

c) What is a typical thickness of the active silicon layers in a conventional crystalline silicon solar cell and in a single junction amorphous silicon solar cell? Which material properties determine the thickness of the active layers?

d) Explain the approaches how to make the crystalline silicon solar cell thinner without influencing the efficiency.

TASK 5: (15 points)

a) Family Black has on the roof of their house place for 4 solar modules (the description of the modules is given below). They decide to place 4 solar modules on their roof using a campaign of Greenpeace, in which their offer a complete solar cell system (with 4 modules) for the price of 1000 €. How many years has to use family Black the solar system to earn the costs of the system back?

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

Given:

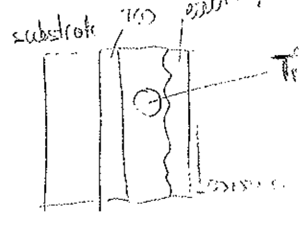
The module efficiency is 12 % and the area of the module is 1 m^2. The lifetime of the module is 25 years. The PV system is placed in The Netherlands where an average price of conventional electricity is 0.22 € per kWh.

TASK 6: (10 Points)

a) Name at least three other types of solar cells than the solar cells based on silicon. What is the status of these solar cells (efficiency)?

b) Draw the basic structure of a Dye-Sensitized solar cell. Explain how the carriers are generated in a Dye-Sensitized solar cell.

a) CIGS 19%, CdTe 16%, Dye-sensitized ~10% max.

b) 

1. CZ method + subst material
2. Slice
3. Polish + grind
4. deposit n+ layer by CVD
5. deposit p+ layer
6. Put 2 electrodes.
7. Encapsulation

TASK 7: (10 Points)

a) What are the major steps in the production of crystalline silicon solar cell (start with the natural source of silicon)? ECN module : slide 26 — feedstock (rocks, quar...

b) Name four major efficiency losses in a crystalline silicon solar cell? Explain them briefly. slide 12, module 7 - losses 1. thermalization process 2. long wavelengths 3. incomplete absorption 4. Reflections

LABORATORY OF ELECTRONIC COMPONENTS, TECHNOLOGY AND MATERIALS

Examination Solar Cells (ET4-149)
Tuesday July 03, 2007, 9:00 –12:00

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: (10 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) Name the main advantages and disadvantages of photovoltaic solar energy?
c) Which photovoltaic technologies are in production at present and which of them dominate the market?
d) Explain the difference between the 1st and 2nd generation of solar cells for terrestrial applications? Which PV technologies are the main representatives of the 1st and 2nd generation of solar cells?
e) What is meant by the **energy pay-back time** of a solar cell?

Answers:

a) The photovoltaic effect means the generation of a potential difference at the junction of two different materials in response to visible or other radiation.

Fundamentally, the device needs to fulfil only two functions: photogeneration of charge carriers (electrons and holes) in a light-absorbing material, and separation of the charge carriers to a conductive contact that will transmit the electricity.

b)

Advantages:

- *environmentally friendly* ✓
- *no noise, no moving parts* ✓
- *no emissions* ✓
- *no use of fuels and water* ✓
- *minimal maintenance requirements* ✓
- *long lifetime, up to 30 years* ✓
- *electricity is generated wherever there is light, solar or artificial* ✓
- *PV operates even in cloudy weather conditions* ✓
- *modular or "custom-made" energy, can be designed for any application from watch to a multi-megawatt power plant* ✓

Cost of a PV system
Excercise:

a) 1. What must be the production costs of a PV system, which generates electricity at a price that is comparable with the price of conventional electricity?
b) What are the costs of this system per Wattpeak?

(Given: The efficiency of PV modules that comprise the PV system is 14% and the lifetime of the modules is 20 years. The PV system is located in The Netherlands where the average price for conventional electricity is 0.10 € per kWh. The average energy per unit area delivered by sunlight during one year is in The Netherlands 1000kWh/(m^2 year). We neglect the conventional electricity price change due to inflation or other circumstances.)

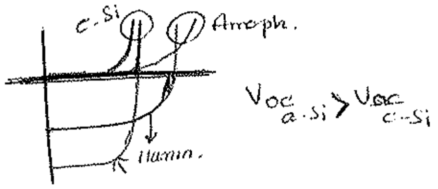
Module area
Excercise:

1. How big area of a roof must be covered with PV modules in order to generate an average household annual use of electricity?
2. How expensive must the PV system be in order to deliver electricity at the same price, as is the price of conventional electricity?

(Given: The efficiency of PV modules that comprise the PV system is 12% and the lifetime of the modules is 20 years. The PV system is located in The Netherlands where the average price for conventional electricity is 0.10 € per kWh and the average energy per unit area delivered by sunlight during one year is 1000 kWh/(m^2 year). The household average electricity use is 2500 kWh per year.

Questions – Organic solar cells

- Which factors do affect the potential in a polymer solar cell?
- Calculate the critical distance in a photoactive blend layer with ε=4.5 at room temperature
- Calculate the minimum thickness of an organic blend layer consisting of a 1 tot 1 mixture of a conjugated polymer and a wide bandgap SC in order to absorb 90 % of the incident light. Neglect the reflection; the polymer has an $\alpha = 18\times10^6 m^{-1}$
- Calculate the average period it takes for an exciton to cross 5 nm in a molecular material. The exciton lifetime is 2 ns and the exciton diffusion length is 25 nm.



b) Draw the band diagrams for both types of solar cells. Sketch the IV characteristics in dark and under standard illumination for both types of solar cells. How can you determine from the IV characteristics, which type of solar cell you measure? → 300–500 nm

c) What is a typical thickness of the active silicon layers in a conventional crystalline silicon → 300–500 μm solar cell and in a single junction amorphous silicon solar cell? Which material properties determine the thickness of the active layers? Diff. length of minority carriers + Absorb. coeff → c-Si; Degradation of a-Si material + Absorpt. coeff → a-Si thickness

d) Explain the approaches how to make the crystalline silicon solar cell thinner without influencing the efficiency. thinner layers with higher efficiency substrates. So, while the effective area that the light hits decreases, the efficiency increases. The total eff. may remain the same.

TASK 5: (15 points)

a) Family Black has on the roof of their house place for 4 solar modules (the description of the modules is given below). They decide to place 4 solar modules on their roof using a campaign of Greenpeace, in which their offer a complete solar cell system (with 4 modules) for the price of 1000 €. How many years has to use family Black the solar system to earn the costs of the system back? 1000 x 0.12 x 4 x 1 m² = 480 kW/year; 480 x 0.2 = 105. €/year; 1000/105.6 = 9.5 year

b) The total use of electricity in the Netherlands is at the moment 80 TWh per year. What is the total area of solar cells that is needed to generate this electricity consumption in the Netherlands. (Use the same modules as family Black) $\frac{80 \times 10^9 kW}{120 kW} = 667 km^2$

Given:
The module efficiency is 12 % and the area of the module is 1 m². The lifetime of the module is 25 years. The PV system is placed in The Netherlands where an average price of conventional electricity is 0.22 € per kWh.

TASK 6: (10 Points)

plastic SC → 5%
polymer SC → 5%
Dye syntisied solar cells → 10%

a) Name at least three other types of solar cells than the solar cells based on silicon. What is the status of these solar cells (efficiency)?

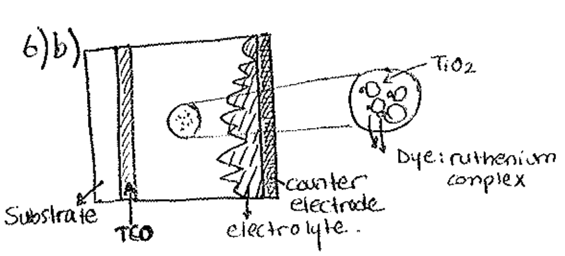
b) Draw the basic structure of a Dye-Sensitized solar cell. Explain how the carriers are generated in a Dye-Sensitized solar cell.

TASK 7: (10 Points)

a) What are the major steps in the production of crystalline silicon solar cell (start with the natural source of silicon)?

b) Name four major efficiency losses in a crystalline silicon solar cell? Explain them briefly.

6)b)

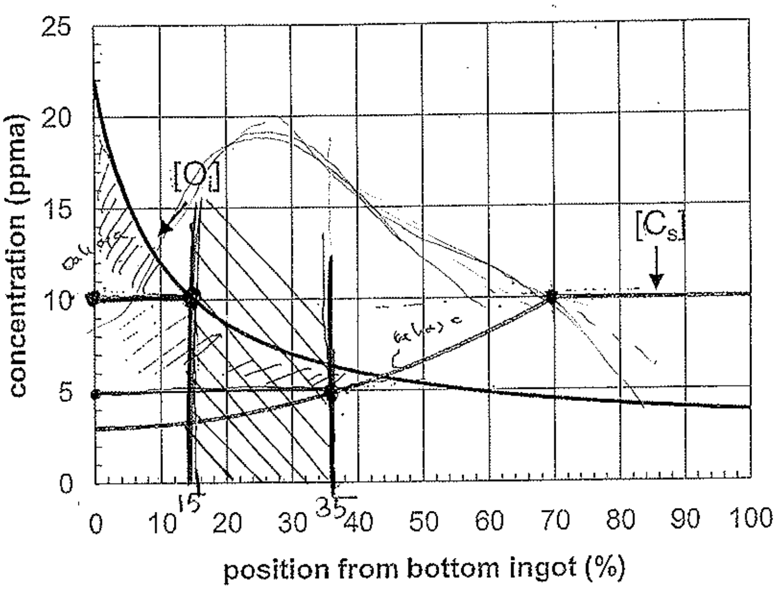


The light is absorbed by the ruthenium dye and the photogenerated electron in the dye is transformed to the conduction band of the TiO2 nanoparticles. The dye is then reduced by the redox electrolyte and as a result the photons are transferred to the counter electrode via the electrolyte.
The electrons in the nanocrystalline TiO2 is transported to the TCO electrode.

7) a) 1- Silicon growth using CZ method and add p-material while growing the silicon ingot.
2- Slice the silicon ingot in the thickness of 300–500 μm
3- Polishing the wafers to remove the non-planer surface
4- Deposit n⁺ layer using CVD methods
5- Create textures on top of n⁺ to reduce the reflection of the incoming light
6- Also put reflective material to the back.
7. Sandwich the structure btw two electrolyde. But the top electrolide should let the light enter the substrate.

7 b) – Loss by the longwavelengths → waves cant absorbed if they have energy lower than the bandgap
– Loss by exeess energy of photons → Energy higher than bandgap energy will be released to the lattice as heat.
– Loss by metal electrode covering the surface
– Loss by incomplete absorption due to the finite thickness.

TASK 5: (15 points)
Silicon wafers are cut from ingots that are about 25 cm high. The concentration of interstitial oxygen [O_i] and substitutional carbon [C_s] is shown in the figure below. The [O_i] above 10 ppma (particle per million atoms) will affect the lifetime of minority carriers negatively. For [C_s] this limit is at 5 ppma. The solid solubility of carbon is about 10 ppma. For higher impurity concentrations silicon carbide precipitates will be formed that will also reduce the lifetime of the charge carriers.



a) Which material parameters of a semiconductor, which are related to the performance of a solar cell, are strongly affected by impurities? Describe the influence shortly.
b) Wafers from which positions of the ingot do you expect to lead to the best efficiencies?
c) Make a sketch of the short-circuit current J_{sc} as a function of the position from the bottom of the ingot. Use arbitrary units for the J_{sc} axis.

TASK 6: (10 points)
a) Family Smith decided to place 4 solar modules (the description of the modules is given below) on their roof using a campaign of the government energy department, in which a complete solar cell system was offered for the price of 1000 €. How many years has to use family Smith 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 and it is expected that it will not change in near future. The annual solar irradiation in the Netherlands corresponds to 1000 equivalent sun hours.)
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 modules that is needed to generate the present consumption of electricity in the Netherlands? (Use the same modules as family Smith)

Given:
The module rated power is 150 Wp and the area is 1.5 m^2. The lifetime of the module is 20 years. In the Netherlands, 1 installed Wp of the above mentioned PV system generates in 1 hour 0.80 Wh under equivalent sun conditions. Tera = 10^{12}.

a) 150 Wp × 1000 × 4 = 600 kW
600 × 0.2 = 120 € /year
1000 / 120 = 8.4 years

b) 150 × 0.8 Wh = 120 Wh
80 × 10^{12} / 120 × 1.5 m^2 = 10^{12} m^2

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 x 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?

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

Hole concentration in the p-type region: $p = N_A = 5 \times 10^{16}\, cm^{-3}$

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: $n = N_D = 3.0 \times 10^{19}\, cm^{-3}$

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:

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

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

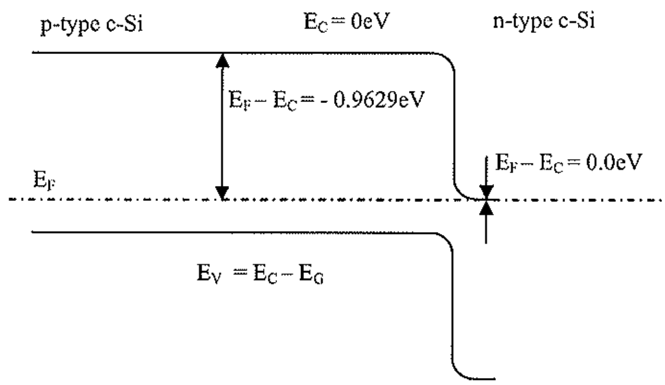


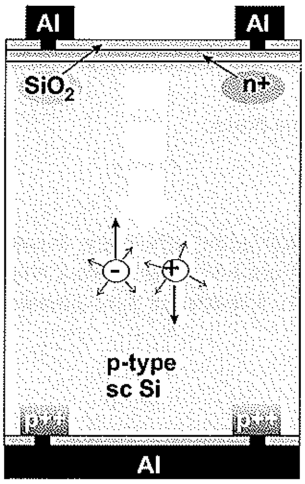
Figure. Band diagram for the crystalline silicon solar cell

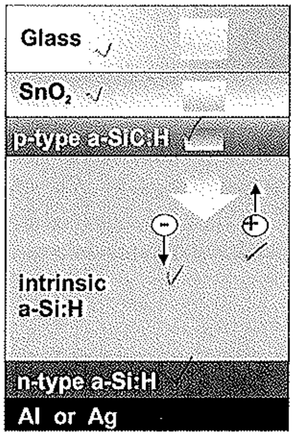
Example/p 3

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.

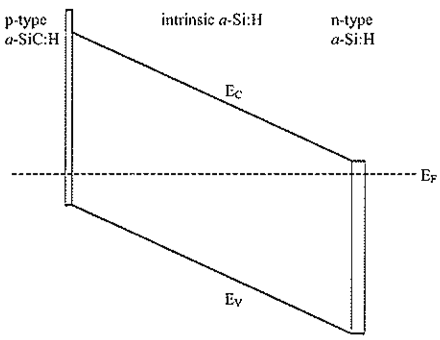


Figure. Band diagram for a-Si:H solar cell

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.

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.

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LABORATORY OF PHOTOVOLTAIC MATERIALS AND DEVICES

Examination Solar Cells (ET4-149)
Friday July 3, 2009, 9.00 – 12.00

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: (10 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 a crystalline silicon solar cell.
c) What are the transport mechanisms of the charge carriers in crystalline silicon? Describe them shortly.
d) What is meant by the ***Energy pay back time*** of a solar cell?

TASK 2: (10 points)
Only photons of appropriate energy can be absorbed and generate the electron-hole pairs in the semiconductor material. It is important to know the spectral distribution of the solar radiation when we design solar cells. Figure 1 shows different spectra referring to the black-body radiation at 6000K, AM0 radiation and the AM1.5 radiation.

Questions:
a) What is the definition of an Optical Air mass? Describe the AM0 and AM1 spectrum.
b) In Figure 1, the spectrum corresponding to AM1.5 shows general attenuation and some gaps, compared to AM0 radiation. Explain the reason.
c) In the case of AM1.5 radiation, what is the photon flux density at the wavelength of $0.4\mu m$. Use Figure 1.
d) Crystalline silicon, whose bond-gap is about 1.12ev, is the material used in the first generation solar cells. Amorphous silicon, whose bond-gap is about 1.7ev, is a kind of promising material for low cost thin-film solar cell representing the second generation solar cells. Estimate the maximum wavelengths which could be absorbed by amorphous and crystalline silicon respectively. (Plank's constant is $6.625\times10^{-34} Js$; the elementary charge is $1.602\times10^{-19} C$; the speed of light in vacuum is $2.998\times10^{8} m/s$)

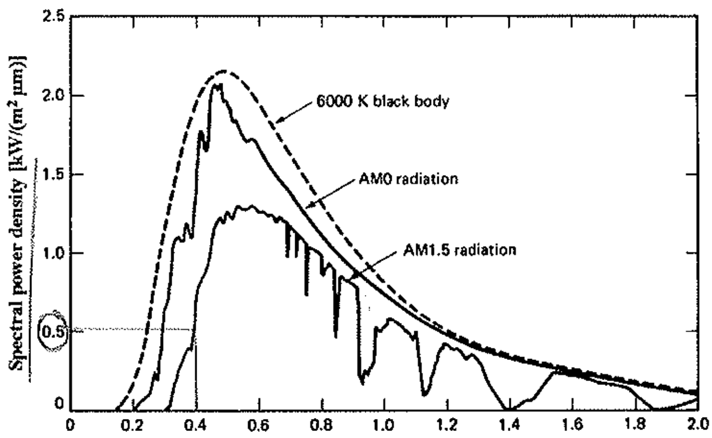

Figure 1

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TASK 7: (15 points)
Design a solar cell system for a summerhouse with 12V nominal operating voltage. The house appliances that are installed in the house are in the table:

DC appliances	***Power consumption [Watts]***	***Using Time /day in hours***
Lamps	60	3
Laptop	150	4
Television	60	3
AC appliances	***Power consumption [Watts]***	***Using Time /day in hours***
Washing machine	400	0.3
Microwave oven	800	0.5
Coffee maker	1000	0.25

960

770

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

Solar insolation details		***The module properties***	
Hours of insolation/day	4 hours	Rated peak power	$150W_P$
		Rated peak voltage	17.0 V
		Rated peak current	8.8 Amp
Battery details		***Inverter details***	
Reserve time	2 days	Inverter system losses	15%
Usable battery power	80%		
Battery system losses	20%		

155.5 A

$\frac{1865\,W}{12} = 155.5 / 4 = 38.8$ req. amp.

$\frac{1865}{12} = 155.5$

20% 186.6

$\frac{186.58}{4}$

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Appendix A

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

SELECTED PROPERTIE OF SILICON (at 300 K)

E_g	energy band gap	1.08 eV
N_C	effective density of states in conduction band	3.0×10^{25} m^{-3} → 3×10^{19} cm^{-3}
N_V	effective density of states in valence band	1.0×10^{25} m^{-3} → 1×10^{19} cm^{-3}
n_i	intrinsic concentration of carriers	1.5×10^{16} m^{-3} → 1.5×10^{10} cm^{-3}
ε_r	relative permittivity	11.7
n	refractive index	3.5 (at 1.1×10^{-6} m wavelength)
μ_e	electron mobility	1350×10^{-4} m^2/Vs
μ_h	hole mobility	480×10^{-4} m^2/Vs
D_e	electron diffusion coefficient	$0.02586 \times \mu_e$
D_h	hole diffusion coefficient	$0.02586 \times \mu_h$

Appendix B

Chapter 2: SOLAR RADIATION

$$\nu = c/\lambda \quad (2.1)$$

$$h\nu = \frac{1}{q}\frac{hc}{\lambda} \quad (2.2)$$

$$\Phi(\lambda) = P(\lambda)\frac{\lambda}{hc} \quad (2.3)$$

$$Air\ mass = (\cos\theta)^{-1} \quad (2.4)$$

Chapter 3: SEMICONDUCTOR MATERIALS FOR SOLAR CELLS

$$E_G = E_C - E_V \quad (3.1)$$

$$g_C(E) = \left(\frac{4\sqrt{2}\,\pi m_n^*}{h^3}\right)^{3/2}(E-E_C)^{1/2} \quad (3.2a)$$

$$g_V(E) = \left(\frac{4\sqrt{2}\,\pi m_p^*}{h^3}\right)^{3/2}(E-E_V)^{1/2} \quad (3.2b)$$

$$f(E) = \frac{1}{1+\exp\left[(E-E_F)/kT\right]} \quad (3.3)$$

$$n = \int_{E_C}^{E_{top}} g_C(E) f(E)\,dE \quad (3.4a)$$

$$p = \int_{E_{bottom}}^{E_V} g_V(E)\left[1-f(E)\right]dE \quad (3.4b)$$

$$n = N_C \exp\left[(E_F - E_C)/kT\right] \qquad \text{for } E_C - E_F \geq 3kT \quad (3.5a)$$

$$p = N_V \exp\left[(E_V - E_F)/kT\right] \qquad \text{for } E_F - E_V \geq 3kT \quad (3.5b)$$

$$np = n_i^2 = N_C N_V \exp\left[(E_V - E_C)/kT\right] = N_C N_V \exp\left[-E_g/kT\right], \quad (3.6)$$

$$n_i = N_C \exp\left[(E_i - E_C)/kT\right] = N_V \exp\left[(E_V - E_i)/kT\right] \quad (3.7)$$

$$E_i = \frac{E_C + E_V}{2} + \frac{kT}{2}\ln\left(\frac{N_V}{N_C}\right) = E_C - \frac{E_g}{2} + \frac{kT}{2}\ln\left(\frac{N_V}{N_C}\right) \quad (3.8)$$

$$\rho = q\left(p + N_D^+ - n - N_A^-\right) \quad (3.9)$$

$$p + N_D^+ - n - N_A^- = 0 \quad (3.10)$$

$$p + N_D - n - N_A = 0 \quad (3.11)$$

$$p + N_D - n = 0. \quad (3.12)$$

$$N_D \approx N_D^+ \approx n \quad (3.13)$$

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$$n = N_C \exp[(E_{FC} - E_C)/kT] \qquad (3.44a)$$
$$p = N_V \exp[(E_V - E_{FP})/kT] \qquad (3.44b)$$

$$n\,p = N_C\,N_V \exp\left[\frac{E_V - E_C}{kT}\right]\exp\left[\frac{E_{FC} - E_{FP}}{kT}\right] = n_i^2 \exp\left[\frac{E_{FC} - E_{FP}}{kT}\right] \qquad (3.45)$$

$$\mathbf{J}_N = n\,\mu_n \nabla E_{FC} \qquad (3.46a)$$
$$\mathbf{J}_P = p\,\mu_p \nabla E_{FV} \qquad (3.46b)$$

$$\frac{\partial n}{\partial t} = \left.\frac{\partial n}{\partial t}\right|_{\text{drift}} + \left.\frac{\partial n}{\partial t}\right|_{\text{diff}} + \left.\frac{\partial n}{\partial t}\right|_{\substack{\text{thermal}\\ \text{R-G}}} + \left.\frac{\partial n}{\partial t}\right|_{\substack{\text{other processes}\\ \text{(photogeneration)}}} \qquad (3.47a)$$

$$\frac{\partial p}{\partial t} = \left.\frac{\partial p}{\partial t}\right|_{\text{drift}} + \left.\frac{\partial p}{\partial t}\right|_{\text{diff}} + \left.\frac{\partial p}{\partial t}\right|_{\substack{\text{thermal}\\ \text{R-G}}} + \left.\frac{\partial p}{\partial t}\right|_{\substack{\text{other processes}\\ \text{(photogeneration)}}} \qquad (3.47b)$$

$$\left.\frac{\partial n}{\partial t}\right|_{\substack{\text{thermal}\\ \text{R-G}}} = -R_N; \qquad \left.\frac{dp}{dt}\right|_{\substack{\text{thermal}\\ \text{R-G}}} = -R_P \qquad (3.48a,b)$$

$$\left.\frac{\partial n}{\partial t}\right|_{\text{other processes}} = G_N; \qquad \left.\frac{\partial p}{\partial t}\right|_{\text{other processes}} = G_P \qquad (3.49a,b)$$

$$\left.\frac{\partial n}{\partial t}\right|_{\text{drift}} + \left.\frac{\partial n}{\partial t}\right|_{\text{diff}} = \frac{1}{q}\nabla\cdot\mathbf{J}_N \qquad (3.50a)$$

$$\left.\frac{\partial p}{\partial t}\right|_{\text{drift}} + \left.\frac{\partial p}{\partial t}\right|_{\text{diff}} = -\frac{1}{q}\nabla\cdot\mathbf{J}_P \qquad (3.50b)$$

$$\frac{\partial n}{\partial t} = \frac{1}{q}\nabla\cdot\mathbf{J}_N - R_N + G_N \qquad (3.51a)$$

$$\frac{\partial p}{\partial t} = -\frac{1}{q}\nabla\cdot\mathbf{J}_P - R_P + G_P \qquad (3.51b)$$

$$\mathbf{J}_N = q\,n\,\mu_n\,\xi + q\,D_N \nabla n \qquad (3.52a)$$
$$\mathbf{J}_P = q\,p\,\mu_p\,\xi - q\,D_p \nabla p \qquad (3.52b)$$

$$\nabla\cdot\xi = \frac{\rho}{\varepsilon_r\varepsilon_0} \qquad (3.53)$$

Chapter 4: SEMICONDUCTOR MATERIALS FOR SOLAR CELLS

$$n = n_{n0} \approx N_D \qquad (4.1a)$$
$$p = p_{n0} \approx n_i^2 / N_D\,. \qquad (4.1b)$$
$$p = p_{p0} \approx N_A \qquad (4.2a)$$
$$n = n_{p0} \approx n_i^2 / N_A\,. \qquad (4.2b)$$

$$\rho(x) = q\,N_D \qquad \text{for } -l_n \le x \le 0 \qquad (4.3a)$$
$$\rho(x) = -q\,N_A \qquad \text{for } 0 \le x \le l_p \qquad (4.3b)$$

$$\frac{d^2\psi}{dx^2} = -\frac{d\,\xi}{dx} = -\frac{\rho}{\varepsilon_r\varepsilon_0}. \qquad (4.4)$$

$$\xi = \frac{1}{\varepsilon_r\varepsilon_0}\int \rho\,dx \qquad (4.5)$$

$$\xi(-l_n) = \xi(l_p) = 0\,, \qquad (4.6)$$

$$\xi(x) = \frac{q}{\varepsilon_r\varepsilon_0} N_D (l_n + x) \qquad \text{for } -l_n \le x \le 0 \qquad (4.7a)$$

$$\xi(x) = \frac{q}{\varepsilon_r\varepsilon_0} N_A (l_p - x) \qquad \text{for } 0 \le x \le l_p \qquad (4.7b)$$

$$N_A\,l_p = N_D\,l_n \qquad (4.8)$$

$$\psi = -\int \xi\,dx \qquad (4.9)$$

$$\psi(l_p) = 0\,. \qquad (4.10)$$

$$\psi(x) = -\frac{q}{2\varepsilon_r\varepsilon_0} N_D\,(x + l_n)^2 + \frac{q}{2\varepsilon_r\varepsilon_0}(N_D l_n^2 + N_A l_p^2) \qquad \text{for } -l_n \le x \le 0 \qquad (4.11a)$$

$$\psi(x) = \frac{q}{2\varepsilon_r\varepsilon_0} N_A (x - l_p)^2 \qquad \text{for } 0 \le x \le l_p \qquad (4.11b)$$

$$\psi_0 = \psi(-l_n) - \psi(-l_p) = \psi(-l_n) \qquad (4.12)$$

$$\psi_0 = \frac{q}{2\varepsilon_r\varepsilon_0}(N_D l_n^2 + N_A l_p^2). \qquad (4.13)$$

$$q\,\psi_0 = E_G - E_1 - E_2 \qquad (4.14)$$

$$q\,\psi_0 = E_G - kT\ln\left(\frac{N_V}{N_A}\right) - kT\ln\left(\frac{N_C}{N_D}\right) = E_G - kT\ln\left(\frac{N_V N_C}{N_A N_D}\right) \qquad (4.15)$$

$$\psi_0 = \frac{kT}{q}\ln\left(\frac{N_A N_D}{n_i^2}\right). \qquad (4.16)$$

$$l_n = \sqrt{\frac{2\varepsilon_r\varepsilon_0}{q}\psi_0 \frac{N_A}{N_D}\left(\frac{1}{N_A + N_D}\right)} \qquad (4.17a)$$

$$l_p = \sqrt{\frac{2\varepsilon_r\varepsilon_0}{q}\psi_0 \frac{N_D}{N_A}\left(\frac{1}{N_A + N_D}\right)} \qquad (4.17b)$$

$$W = l_n + l_p = \sqrt{\frac{2\varepsilon_r\varepsilon_0}{q}\psi_0 \left(\frac{1}{N_A} + \frac{1}{N_D}\right)} \qquad (4.18)$$

$$\xi_{\max} = \sqrt{\frac{2q}{\varepsilon_r\varepsilon_0}\psi_0 \left(\frac{N_A N_D}{N_A + N_D}\right)} \qquad (4.19)$$

$$J = J_{rec} - J_{gen} = 0 \qquad \text{for } V_a = 0\text{ V} \qquad (4.20)$$

$$J_{rec}(V_a) = J_{rec}(V_a = 0)\exp\left(\frac{qV_a}{kT}\right) \qquad (4.21)$$

$$J_{gen}(V_a) \approx J_{gen}(V_a = 0) \qquad (4.22)$$