Solar Energy Tutorial 6 08.02.2024

1) Answer: b is right

Heating losses are higher in solar cell A ($E_g = 1eV$) than solar cell B ($E_g = 1,7eV$).

2)

Answer: GaAs: $d = 1,5\mu m$ InP: $d = 0,58\mu m$ Ge: $d = 0,38\mu m$ Si: $d = 25,6\mu m$

The Lambert-Beer law describes how the intensity of the light beam decays as it propagates through an absorbing medium with a certain absorption coefficient $\alpha(\lambda)$:

$$I(d) = I_0 \, e^{-\alpha(\lambda) d}$$

For a layer of thickness d to absorb 90% of the incoming light $I = 0,1 I_0$:

$$d = -\frac{\ln(0,1)}{\alpha(\lambda)}$$

First the absorption coefficient is taken from the figure, after converting the energy of the photons into wavelength via:

$$\cancel{\lambda[nm]} = \lambda(nm) = \frac{hc}{q E_{ph}} = \frac{6,626 \cdot 10^{-34} Js \cdot 2,998 \cdot 10^{8} m/s}{1,602 \cdot 10^{-19} C \cdot 1,55 eV} = 800 nm$$

Taking into account that the y-axis is plotted in a logarithmic scale, the absorption coefficient can be estimated and the required thickness of each material can be calculated:

GaAs: $\alpha(800nm) = 1,5 \cdot 10^{4} \, 1/cm$ $\quad d = -\frac{\ln(0,1)}{1,5 \cdot 10^{4} \, 1/cm} = 1,5\mu m$

InP: $\alpha(800nm) = 4 \cdot 10^{4} \, 1/cm$ $\quad d = -\frac{\ln(0,1)}{4 \cdot 10^{4} \, 1/cm} = 0,58\mu m$

Ge: $\alpha(800nm) = 6 \cdot 10^{4} \, 1/cm$ $\quad d = -\frac{\ln(0,1)}{6 \cdot 10^{4} \, 1/cm} = 0,38\mu m$

Si: $\alpha(800nm) = 9 \cdot 10^{2} \, 1/cm$ $\quad d = -\frac{\ln(0,1)}{9 \cdot 10^{2} \, 1/cm} = 25,6\mu m$

3)

a) Answer: $P = 900 W_p$

Since the inverter is able to handle $900 W_p$, the number of panels will be calculated as

$$N_{panels} = \frac{900 W_p}{75 W_p} = 12$$

Each panel is $0,5 m^2$, so it will equal a total of $6 m^2$ for all panels. Considering the rooftop area of $10 m^2$, it is possible to install $900 W_p$.

b) Answer: $600 W_p$

Since the inverter is able to handle $900 W_p$, the number of panels will be calculated as

$$N_{panels} = \frac{900 W_p}{30 W_p} = 30$$

Each panel is $0,5 m^2$, so it will equal a total of $15 m^2$ for all the panels. Considering the rooftop area of $10 m^2$, it isn't possible to install 30 panels. Therefore, the maximum possible peak power that can be installed will be determined by the rooftop area as:

$$N_{panels} = \frac{10 m^2}{0,5 m^2} = 20 \qquad P = 20 \cdot 30 W_p = 600 W_p$$

3)

c) Answer: Price $= 0,11 \frac{€}{kWh}$

The total cost of system A will be:

$$Cost = N_{panels} \cdot \frac{Price}{Panel} + other\ costs = 12 \cdot 60€ + 1000€ = 1720€$$

To calculate the price of electricity of the system, this cost will be divided by the total amount of energy that the system will produce in the 20 years of it's livetime:

$$E = 900W_p \cdot 850 \frac{Wh}{W_p \cdot year} \cdot 20 years = 15300 kWh$$

$$Price = \frac{1720€}{15300 kWh} = 0,11 \frac{€}{kWh}$$

d) Answer: Price $= 0,12 \frac{€}{kWh}$

The total cost of the system B will be:

$$Cost = N_{panels} \cdot \frac{Price}{Panel} + other\ costs = 20 \cdot 20€ + 1000€ = 1400€$$

To calculate the price of electricity of the system, this costs will be divided by the total amount of energy that the system will produce in the 20 years of it's livetime:

$$E = 600W_p \cdot 1,1 \cdot 850 \frac{Wh}{W_p \cdot year} \cdot 20 years = 11220 kWh$$

$$Price = \frac{1400€}{11220 kWh} = 0,12 \frac{€}{kWh}$$

e) Answer: Payback time $= 8,3$ years

The total cost of the system including subsidies will be:

$$Cost = 0,85 \cdot \left(N_{panels} \cdot \frac{Price}{panel} + other\ costs \right) = 0,85 \cdot (12 \cdot 60€ + 1000€) = 1462€$$

To calculate the time needed to earn the investment back, the energy produced per year and the electricity cost that this would imply if the system would not be installed should be determined. Such calculations assume that all the energy produced by the solar panel is used:

$$E = 900W_p \cdot 850 \frac{Wh}{W_p \cdot year} = 765 \frac{kWh}{year}$$

$$Cost\ of\ electricity = 765 \frac{kWh}{year} \cdot 0,23 \frac{€}{kWh} = 175,95 \frac{€}{year}$$

By dividing the total investment costs by the annual electricity costs, the payback time can be determined:

$$Payback\ time = \frac{1462€}{175,95 \frac{€}{year}} = 8,3\ years$$

3)

f) Answer: Payback time = 9,2 years

The total cost of the system including subsidies will be

$$Cost = 0{,}85 \cdot \left(N_{panels} \cdot \frac{Price}{panel} + other\ costs\right) = 0{,}85 \cdot (20 \cdot 20€ + 1000€) = 1190€$$

To calculate the time needed to earn the investment back, the energy produced per year and the electricity cost that this would imply if the system would not be installed should be determined. Such calculations assume that all the energy produced by the solar panels is used:

$$E = 600\,W_p \cdot 1{,}1 \cdot 850 \frac{Wh}{W_p \cdot year} = 561 \frac{kWh}{year}$$

$$cost\ of\ electricity = 561 \frac{kWh}{year} \cdot 0{,}23 \frac{€}{kWh} = 129{,}03 \frac{€}{year}$$

By dividing the total investment costs by the annual electricity costs, the payback time can be determined:

$$Payback\ time = \frac{1190€}{129{,}03 \frac{€}{year}} = 9{,}2\ years$$

4)

a) Answer: $E_g = 1{,}9\,eV$

To calculate the bandgaps, we should take into account the wavelength until which a certain junction absorbs light.

Junction A absorbs light (has a non-zero EQE) until $\lambda = 650\,nm$. The wavelength can be converted into energy by using the relation:

$$E_g = \frac{hc}{\lambda \cdot q} = \frac{6{,}626 \cdot 10^{-34}\,Js \cdot 2{,}998 \cdot 10^{8}\,\frac{m}{s}}{650 \cdot 10^{-9}\,m \cdot 1{,}602 \cdot 10^{-19}\,C} = 1{,}9\,eV$$

b) Answer: $E_g = 1{,}46\,eV$

Junction B absorbs light (has a non-zero EQE) until $\lambda = 850\,nm$. The wavelength can be converted into energy by using the relation:

$$E_g = \frac{h \cdot c}{\lambda \cdot q} = \frac{6{,}626 \cdot 10^{-34}\,Js \cdot 2{,}998 \cdot 10^{8}\,\frac{m}{s}}{850 \cdot 10^{-9}\,m \cdot 1{,}602 \cdot 10^{-19}\,C} = 1{,}46\,eV$$

c) Answer: $E_g = 0{,}99\,eV$

Junction C absorbs light (has a non-zero EQE) until $\lambda = 1250\,nm$. The wavelength can be converted into energy by using the relation:

$$E_g = \frac{h \cdot c}{\lambda \cdot q} = \frac{6{,}626 \cdot 10^{-34}\,Js \cdot 2{,}998 \cdot 10^{8}\,\frac{m}{s}}{1250 \cdot 10^{-9}\,m \cdot 1{,}602 \cdot 10^{-19}\,C} = 0{,}99\,eV$$

4)

d) Answer: C

In a multi-junction solar cell, the cell with the highest band gap is placed at the top, and the cell with the lowest band gap is placed at the bottom. Therefore, junction A acts as the top cell, junction B as the middle cell, and junction C as the bottom cell.

e) Answer: $J_{sc,A} = 10,42 \frac{mA}{cm^2}$ $J_{sc,B} = 12,10 \frac{mA}{cm^2}$ $J_{sc,C} = 17,92 \frac{mA}{cm^2}$

The ~~shorted~~ short circuit current ~~dens~~ density can be calculated as:

$$J_{sc} = q \cdot \int EQE(\lambda) \cdot \Phi_{ph,\lambda} \, d\lambda = q \, EQE \, \Phi_{ph}$$

Junction A has an EQE of 0,7 between a wavelength of 300nm and 650nm. This gives:

$$J_{sc,A} = 1,602 \cdot 10^{-19} C \cdot 0,7 \cdot 9,3 \cdot 10^{20} \frac{1}{m^2 s} = 104,2 \frac{A}{m^2} = 10,42 \frac{mA}{cm^2}$$

Junction B has an EQE of 0,9 between a wavelength of 650nm and 850nm. This gives:

$$J_{sc,B} = 1,602 \cdot 10^{-19} C \cdot 0,9 \cdot 8,4 \cdot 10^{20} \frac{1}{m^2 s} = 121,0 \frac{A}{m^2} = 12,10 \frac{mA}{cm^2}$$

Junction C has an EQE of 0,8 between a wavelength of 850nm and 1250nm. This gives:

$$J_{sc,C} = 1,602 \cdot 10^{-19} C \cdot 0,8 \cdot 1,4 \cdot 10^{20} \frac{1}{m^2 s} = 179,2 \frac{A}{m^2} = 17,92 \frac{mA}{cm^2}$$

f) Answer: $\eta = 17\%$

The efficiency is calculated as: $\eta = \frac{J_{sc} \cdot V_{oc} \cdot FF}{P_{in}}$

The open circuit voltages are

$$V_{oc,A} = \frac{1,9 eV}{2q} = 0,95V \quad V_{oc,B} = \frac{1,46 eV}{2q} = 0,73V \quad V_{oc,C} = \frac{0,99 eV}{2q} = 0,495V$$

Since the cells are connected in series, the short circuit current density of the multi-junction cell will be limited by the lowest short circuit density. On the other hand, the open circuit voltages will add up. Thus:

$$\eta = \frac{J_{sc} \cdot V_{oc} \cdot FF}{P_{in}} = \frac{J_{sc,A} \cdot (V_{oc,A} + V_{oc,B} + V_{oc,C}) \cdot FF}{P_{in}} = \frac{10,42 mA \cdot \frac{1}{cm^2} (0,95V + 0,73V + 0,495V) \cdot 0,75}{100 \frac{mW}{cm^2}} = 0,1699 = 17\%$$

5)

a) Answer: spectral range A

The bandgap is a measure for lowest the energy of a photon that can be absorbed in the material. This corresponds to a wavelength which is calculated as

$$\lambda = \frac{hc}{qE_g} = \frac{6,626 \cdot 10^{-34} Js \cdot 2,998 \cdot 10^8 \frac{m}{s}}{1,602 \cdot 10^{-19} C \cdot 2,0 eV} = 620nm$$

This corresponds to spectral range A.

5)

b) Answer: $J_{sc} = 10,4 \frac{mA}{cm^2}$

The short~~est~~ circuit current density can be calculated as:

$$J_{sc} = q \int EQE(\lambda) \cdot \Phi_{ph,\lambda} \, d\lambda = q \cdot EQE \cdot \Phi_{ph}$$

The solar cell has an EQE of 0,65 between a wavelength of 0nm and 620nm. This gives:

$$J_{sc} = 1,602 \cdot 10^{-19} C \cdot 0,65 \cdot 10 \cdot 10^{20} \frac{1}{m^2 s} = 104 \frac{A}{m^2} = 10,4 \frac{mA}{cm^2}$$

c) Answer: $\eta = 8,3\%$

The efficiency is calculated as:

$$\eta = \frac{J_{sc} \cdot V_{oc} \cdot FF}{P_{in}}$$

The open circuit voltage is calculated with the given equation:

$$V_{oc} = \frac{2eV}{2q} = 1V$$

Therefore the efficiency is:

$$\eta = \frac{10,4 \frac{mA}{cm^2} \cdot 1V \cdot 0,8}{100 mW \cdot \frac{1}{cm^2}} = 0,083 = 8,3\%$$

d) Answer: spectral range B

In order for the photon emitted by the upconverter to be absorbed in the a-SiC:H layer, the sum of the energy of the two (lower-energy) photons must be at least equal to the SiC:H bandgap. Therefore, the minimum energy that each of the two photons must carry is:

$$\frac{2eV}{2 \text{ photons}} = 1 \frac{eV}{\text{photon}} \qquad \lambda = \frac{6,626 \cdot 10^{-34} Js \cdot 2,998 \cdot 10^{8} \frac{m}{s}}{1,602 \cdot 10^{-19} C \cdot 1eV} = 1240nm$$

Since we assume that photons up to 620nm are absorbed in the ~~SiH:C~~ SiC:H layer, ~~the photons~~ the photons can be up-converted in spectral range B.

e) Answer: $J_{sc} = 16 \frac{mA}{cm^2}$, $\eta = 10,4\%$

The short circuit current density can be calculated as:

$$J_{sc} = q \int EQE(\lambda) \Phi_{ph,\lambda} \, d\lambda = q \, EQE \left(\Phi_{ph_A} + \frac{1}{2} \Phi_{ph_B} \right)$$

Take into account that the factor 1/2 in front of the second integral is due to the fact that the upconverter converts two low energy electrons into one high energy electron (we lose half of the photons flux). The solar cell has an EQE of 0,65 between a wavelength of 0nm and 1240nm. This gives:

$$J_{sc} = 1,602 \cdot 10^{-19} C \cdot 0,65 \left(10 \cdot 10^{20} \frac{1}{m^2 s} + \frac{1}{2} \cdot 11 \cdot 10^{20} \frac{1}{m^2 s} \right) = 160 \frac{A}{m^2} = 16,0 \frac{mA}{cm^2}$$

The efficiency is calculated as:

$$\eta = \frac{16 mA \cdot \frac{1}{cm^2} \cdot 1V \cdot 0,65}{100 \frac{mW}{cm^2}} = 0,104 = 10,4\%$$

5)

f) Answer: spectral range C

In order for the photon emitted by the second upconverter to be absorbed in the a-SiC:H layer, the sum of the energy of the three (lower-energy) photons must be at least equal to the a-SiC:H bandgap. Therefore, the minimum energy that each of the three photons must carry is:

$$\frac{2eV}{3\,photons} = 0{,}667\frac{eV}{photon} \qquad \lambda = \frac{6{,}626\cdot 10^{-34}\,Js \cdot 2{,}998\cdot 10^{8}\,\frac{m}{s}}{1{,}602\cdot 10^{-19}\,C \cdot 0{,}667\,eV} = 1860\,nm$$

Since we assume that photons up to 620nm are absorbed in the a SiC:H layer and that photons up to 1240nm are converted in upconverter 1, the photons can be up-converted in spectral range C.

g) Answer: $J_{sc} = 18\frac{mA}{cm^2}$ $\quad \eta = 11{,}7\%$

The short circuit density can be calculated as:

$$J_{sc} = q\int EQE(\lambda)\cdot \Phi_{ph,\lambda}\, d\lambda = q\, EQE\left(\Phi_{ph,A} + \frac{1}{2}\Phi_{ph,B} + \frac{1}{3}\Phi_{ph,C}\right)$$

Take into account that the factor 1/3 in front of the third integral is due to the fact that the upconverter converts the lower-energy electrons into one hig energy electron (we lose one-third of the photon flux). The solar cell has an EQE of 0,65 between a wavelength of 0nm and 1860nm. This gives:

$$J_{sc} = 1{,}602\cdot 10^{-19}\,C\cdot 0{,}65\cdot\left(10\cdot 10^{20}\frac{1}{m^2 s} + \frac{1}{2}\cdot 11\cdot 10^{20}\frac{1}{m^2 s} + \frac{1}{3}\cdot 6\cdot 10^{20}\frac{1}{m^2 s}\right) = 180\frac{A}{m^2} = 18{,}0\frac{mA}{cm^2}$$

The efficiency is calculated as:

$$\eta = \frac{18\frac{mA}{cm^2}\cdot 1V\cdot 0{,}65}{100mW\cdot\frac{1}{cm^2}} = 0{,}117 = 11{,}7\%$$

KÜHNE+NAGEL