Solution 10

Exercise 1:

a) A photodiode is basically a solar cell that is used to get information about the incoming light from the measured current. It consists of a p-n junction for c-Si, with an additional intrinsic layer between the p- and n-layer for amorphous materials. Photodiodes have therefore always a built-in electric field that collects the charges; It is usually supported by a bias voltage. Assuming an external quantum efficiency of 1, each incident photon creates an e^-/h^+-pair, which provides the current. No additional current can flow, as the p- and n-layers are blocking contacts prohibiting inflow of further charges.

In contrast to that, photoconductors consist only of the intrinsic layer or (undoped) c-Si. Therefore, they have no built-in electric field, external voltage must be applied to collect the charges. As for photodiodes, each incident photon can create an e^-/h^+-pair, which however results in a far higher current than the photodiode. This is due to the different mobility of electrons and holes: While the slower carrier (the hole for both crystalline and amorphous silicon) is still travelling towards the ohmic contact, the faster one has already reached the contact and recombined there. To keep the charge neutrality at any time inside the photoconductor, another electron is reinjected from the external circuit inside the photoconductor, which makes the total current in the external circuit larger than in the photodiode case.

b) The photodiode is governed by the Shockley equation

$$J_{\text{dark}} = J_0 \left[\exp\left(\frac{qV}{\eta k_B T}\right) - 1\right] \tag{1}$$

in the dark and

$$J_{\text{ill}} = J_{\text{L}} - J_0 \left[\exp\left(\frac{qV}{\eta k_B T}\right) - 1\right] \tag{2}$$

under illumination (principle of superposition). Thus,

$$\frac{J_{\text{ill}}}{J_{\text{dark}}} = \frac{J_L}{J_0 \left[\exp\left(\frac{qV}{\eta k_B T}\right) - 1\right]} - 1. \tag{3}$$

For J_0, the approximation presented in the chapter `1-Photovoltaics and solar cells` (slide 18) can be used (J_0 as function of E_g), leading to the following values:

$$J_0^{\text{c-Si}} = 4.97 \times 10^{-10}\,\text{A}\,\text{m}^{-2}$$

$$J_0^{\text{a-Si}} = 5.97 \times 10^{-21}\,\text{A}\,\text{m}^{-2}$$

The diode ideality factor η is about 1 for c-Si, whereas for a-Si any value between 1.2 and 1.9 is possible (here we take 1.6). However, it is not a crucial parameter for the approximation we want to obtain in that exercise. The only remaining unknown parameter is therefore the current due to illumination, J_L, which can be approximated as following:

$$\begin{aligned} J_\mathrm{L} &= J_\mathrm{sc} && (4)\\ &= \int_\mathbb{R} spec(\lambda)\cdot SR(\lambda)\,\mathrm{d}\lambda && (5)\\ &= \int_\mathbb{R} spec(\lambda)\cdot \frac{EQE(\lambda)\cdot q}{E(\lambda)}\,\mathrm{d}\lambda && (6)\\ &= 1000\,\mathrm{W\,m^{-2}}\cdot\frac{0.8\cdot q\cdot 632\,\mathrm{nm}}{hc} && (7)\\ &= 407\,\mathrm{A\,m^{-2}} = 40.7\,\mathrm{mA\,cm^{-2}} && (8)\end{aligned}$$

assuming an EQE (for amorphous silicon at 632 nm) = 0.8. In the case of c-Si, $EQE(632\,\mathrm{nm})$ would be slightly higher. However, 0.8 has been used for the further calculations.
We remind you that the spectral response is defined as:

$$SR(\lambda) = \frac{EQE(\lambda)\cdot q}{E(\lambda)} \tag{9}$$

The thickness of the devices plays a minor role here because complete absorption can be assumed for the given thicknesses. For thinner devices EQE would be lower. Assuming:

$$\begin{aligned} E_\mathrm{g}^\text{c-Si} &= 1.1\,\mathrm{eV} && (10)\\ E_\mathrm{g}^\text{a-Si} &= 1.75\,\mathrm{eV} && (11)\\ \eta^\text{c-Si} &= 1 && (12)\\ \eta^\text{a-Si} &= 1.6 && (13)\end{aligned}$$

one gets

$$\frac{J_\mathrm{ill}}{J_\mathrm{dark}} \cong \begin{cases} -8.2\times 10^{11} & \text{for c-Si}\\ -6.8\times 10^{22} & \text{for a-Si.}\end{cases} \tag{14}$$

While the value for crystalline silicon can approximately be achieved, the value for amorphous silicon is too large by many orders of magnitude. Here, the one-diode model does not fit at all (e.g. recombination currents play a major role). Nevertheless, if the one-diode model is fitted to an experimental curve, one gets a more realistic value of $J_0^\text{a-Si} \approx 10^{-9}\,\mathrm{mA\,cm^{-2}}$ and with it $\frac{J_\mathrm{ill}}{J_\mathrm{dark}} \approx -4\cdot 10^{10}$ for a-Si:H.

c) One can treat photoconductors as light-dependent resistors:

$$\frac{J_\mathrm{ill}}{J_\mathrm{dark}} = \frac{\sigma_\mathrm{ill}}{\sigma_\mathrm{dark}} = \frac{\sigma_\mathrm{photo}+\sigma_\mathrm{dark}}{\sigma_\mathrm{dark}}. \tag{15}$$

From `k-Transport and recombination` (slide 31) we know that:

$$
\begin{aligned}
\sigma_{\mathrm{dark}} &= \sigma_0 e^{-\frac{E_{\mathrm{a}}}{kT}} \quad \text{with} && (16)\\
& E_{\mathrm{a}} = \frac{E_{\mathrm{g}}}{2} \quad \text{(for intrinsic material)}, && (17)\\
& \sigma_0^{\text{c-Si}} = 11\,400\,\Omega^{-1}\,\mathrm{cm}^{-1} \quad \text{(slide 36)} && (18)\\
& \sigma_0^{\text{a-Si}} = 150\,\Omega^{-1}\,\mathrm{cm}^{-1} \quad \text{(slide 36)} && (19)\\
\sigma_{\mathrm{dark}}^{\text{c-Si}} &= 6.6\times 10^{-6}\,\Omega^{-1}\,\mathrm{cm}^{-1} && (20)\\
\sigma_{\mathrm{dark}}^{\text{a-Si}} &= 3\times 10^{-13}\,\Omega^{-1}\,\mathrm{cm}^{-1} && (21)\\
\sigma_{\mathrm{photo}} &= qG(\mu_{\mathrm{n}}\tau_{\mathrm{n}} + \mu_{\mathrm{p}}\tau_{\mathrm{p}}) \quad \text{with} && (22)\\
& \mu_{\mathrm{n}}^{\text{c-Si}}\tau_{\mathrm{n}}^{\text{c-Si}} = 3\times 10^{-3}\,\mathrm{cm}^2\,\mathrm{V}^{-1} && (23)\\
& \mu_{\mathrm{p}}^{\text{c-Si}}\tau_{\mathrm{p}}^{\text{c-Si}} = 5\times 10^{-3}\,\mathrm{cm}^2\,\mathrm{V}^{-1} && (24)\\
& \mu_{\mathrm{n}}^{\text{a-Si}}\tau_{\mathrm{n}}^{\text{a-Si}} = 3\times 10^{-6}\,\mathrm{cm}^2\,\mathrm{V}^{-1} && (25)\\
& \mu_{\mathrm{p}}^{\text{a-Si}}\tau_{\mathrm{p}}^{\text{a-Si}} = 1\times 10^{-7}\,\mathrm{cm}^2\,\mathrm{V}^{-1} && (26)\\
\sigma_{\mathrm{photo}}^{\text{c-Si}} &= 3.3\times 10^{-2}\,\Omega^{-1}\,\mathrm{cm}^{-1} && (27)\\
\sigma_{\mathrm{photo}}^{\text{a-Si}} &= 1.3\times 10^{-3}\,\Omega^{-1}\,\mathrm{cm}^{-1} && (28)\\
& && (29)
\end{aligned}
$$

Assuming again complete absorption of the incident light within the thickness d, the generation rate G can be calculated as

$$G = \frac{J_{\mathrm{sc}}}{d\cdot q}. \tag{30}$$

With that, one gets finally

$$\frac{J_{\mathrm{ill}}}{J_{\mathrm{dark}}} \cong \begin{cases} 4.97\cdot 10^3 & \text{for c-Si} \\ 4.22\cdot 10^9 & \text{for a-Si.} \end{cases} \tag{31}$$

Comparing with the photodiode case, one can see that diodes are better suited to detect weak signals than photoconductors.

Exercise 2: The working principle is explained in the course n - *Photodetectors and photoconductors* on slide 39.
The drift mobility μ^d, the electric field E and the drift velocity v_d are related via

$$v_d = \mu^d \cdot E. \tag{32}$$

In our 1D case, the electric field E can be expressed as

$$E = \frac{V_0}{w}, \tag{33}$$

where V_0 is the voltage across the layer and w its thickness. Using

$$v_d = \frac{w}{\tau} \tag{34}$$

we finally obtain

$$\mu^d = \frac{w^2}{V_0 \tau}. \tag{35}$$

When inserting the numerical values, we obtain a required drift mobility of $\mu^d \geq 1.6 \times 10^{-7}\,\mathrm{cm^2\,V^{-1}\,s^{-1}}$. This implies that semiconductors with very low mobility can be used for xerography.