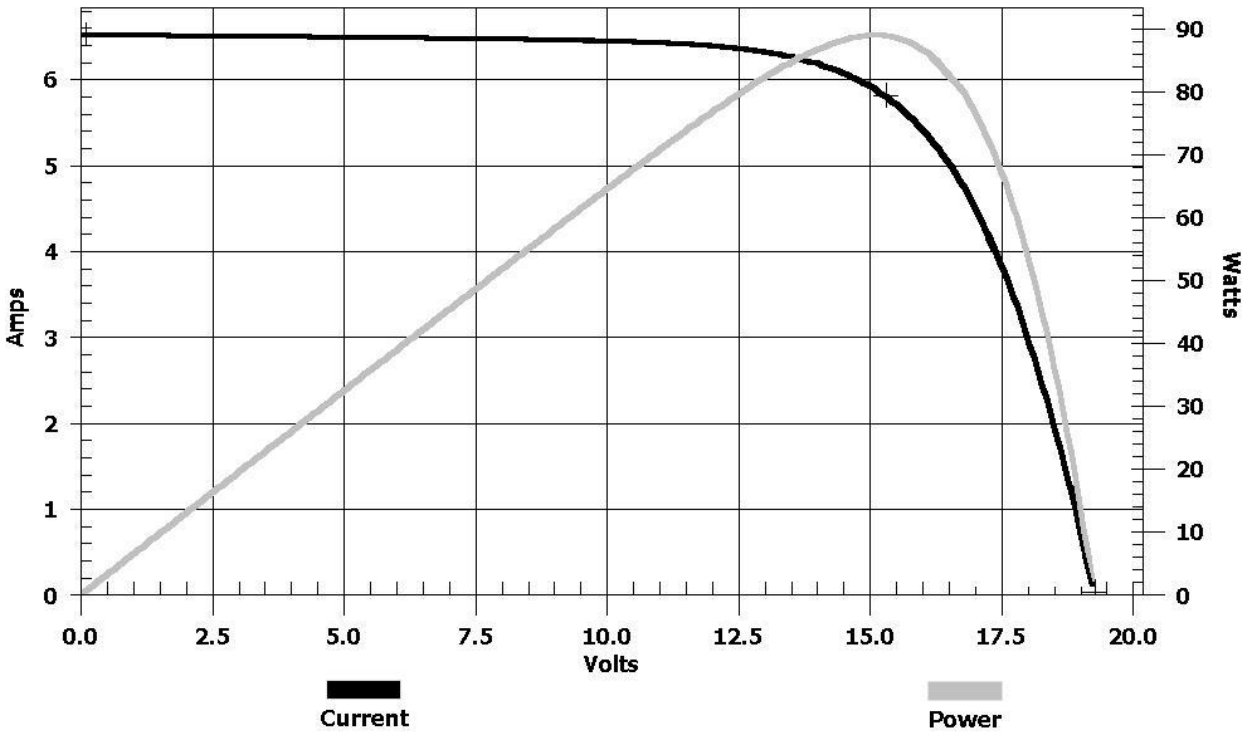
1. Explain briefly (6 p)

   a) N-type doping of silicon
   b) Electron diffusion length
   c) Multi-junction solar cell
   d) Parallel and series connection solar cells to modules
   e) Grid-connected photovoltaic system
   f) Grid parity

2. The figure below shows the current – voltage (IV) curve of a solar module (black curve) and corresponding power curves (power as the function of voltage, gray curve), measured at the standard test conditions (STC, radiation intensity 1000 W/m^2, temperature 25°C). The dimensions of the module are 600 x 1000 mm. Estimate approximately from the graph the open circuit voltage (V_{OC}), short circuit current (I_{SC}), fill factor (*FF*), and energy conversion efficiency (η) of the module in the following cases a) and b)

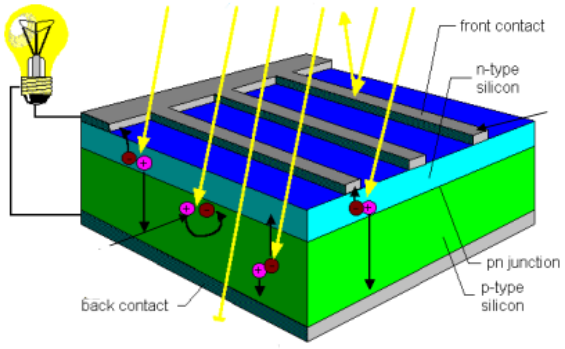
   a) The initial case, as shown in the figure (2 p),
   b) Otherwise the same, but an additional series resistance (R_S) of 1 Ω due to a bad external electrical contact is affecting the performance of the module (2 p)
   c) What is the operating point (current, voltage, power) when a load resistance of 10 Ω is connected to the solar module in case a)? (1 p)
   d) What value of the load resistance would draw the maximum power from the solar cell? (1 p)

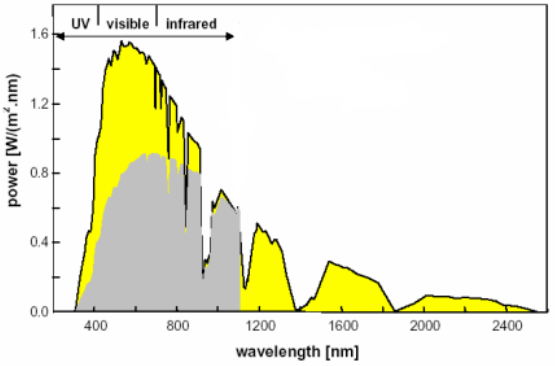


3. Crystalline silicon solar cells, as well as many other solar cells that are based in inorganic semiconductors, are often called pn-junction solar cells.

   a) Explain briefly the main aspects of the working principle of a pn-junction solar cell (excluding losses, which are the topic of the next question) (2 p)
   b) The width W of the depletion zone of a pn-junction is 10 µm, dopant density in n-side (N_D) is $2.3 \cdot 10^{23}/m^3$ and in p-side (N_A) $8.6 \cdot 10^{21}/m^3$. Assume that the net charge density inside the depletion zone is constant and outside it zero. How far the depletion zone reaches to n-side and how far to the p-side? (2 p)
   c) Coordinate x is defined perpendicular to the plane of pn-junction. Deduce the equation for the electric field of the junction as a function of x, when the dopant densities are known. Again, the net charge density inside the depletion zone is constant and zero outside the zone. (2 p)

4. What are the main performance losses that limit the maximum theoretical energy conversion efficiency of crystalline silicon solar cells below 33 % and that of practical record solar cells to ca. 26 %? Name and briefly explain these loss processes, and identify the key material properties that determine them. What are the two fundamental loss factors that already together limit the efficiency to ca. 45 %? The figures below are given as a hint. (6 p)





5. Design and sketch a stand-alone a PV system for a village electrification application in Africa. The daily average solar radiation is 6 kWh/m^2 and the daily average demand of electricity is 5000 Wh. The photovoltaic modules available for the project have rated power of 120 W, and their maximum power point voltage and current are V_{MPP} = 34.2 V and I_{MPP} = 3.5 A, respectively. You can choose between 12 V and 24 V batteries. The required reserve time (operation without PV) is 3 days. (6p)