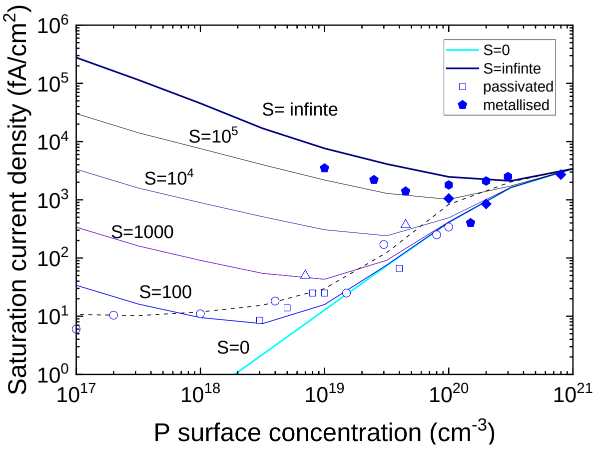
Exercise 2.1: Selective emitter (5-7 min)

In the development of c-Si solar cells, much of effort was devoted to the front contact. Highly diffused emitters like the phosphorous diffusion profiles shown in the course were already very early replaced by *passivated emitters*, and eventually further improved on by the introducing *selective emitters*.

a) Design a sketch of the front region of a c-Si solar cell, showing the *pn*-junction between wafer and the diffused region, the local contacts to the silver finger metallisation, and the passivated region between the fingers.

b) Using the diagram below,[1] explain the working principle of a passivated emitter. Discuss what motivated the development of passivated emitters.



c) Assume a *passivated emitter* with reduced surface concentration of $N_D = 10^{19}\ \mathrm{cm}^{-3}$. Project the j_0 by using an area weighted sum of $j_{0,met}$ and $j_{0,pass}$, assuming that the silver fingers cover an area of 10%.

d) Explain the working principle of a *selective emitter* that combines highly doped regions below the fingers and lowly doped regions with passivation. Point out the additional improvement that is possible.

[1] The symbols refer to experimental data digitized from King, TED (1980) and from Kerr, JAP (2001). The lines refer to a simple model with the geometry factor G_F, assuming constant donor density N_D equal to the surface concentration.

Exercise 2.2: Efficiency limit of crystalline silicon (3 people, 15-20 min)

In this group exercise for three people, you will derive the upper limit for crystalline silicon. The derivation splits into three tasks which you have to combine.

Basic idea: For high efficiency we have to create a high photocurrent, but this requires a large device thickness because silicon is a weak absorber. Consequently, the generation would spread over a large volume, resulting in a low injection level and thus a low V_{oc}. A thinner cell will generate a lower photocurrent, but it may have a higher V_{oc}. Construct a (shared) spreadsheet that finds the optimum of this trade-off. For the presentation, focus on explaining your reasoning and show a only minimum of formulae.

a) Determine the maximum photocurrent for a given cell thickness.
Calculate the absorption with the multipass formula of Deckman, APL (1983) with the absorption coefficient tabulated in Green, SolMat (2008), assuming zero reflection at the front and zero absorption at the rear. Convolute the result with the AM1.5 spectrum https://rredc.nrel.gov/solar//spectra/am1.5/ASTMG173/ASTMG173.html and integrate in the relevant wavelength range for silicon. Repeat for different thicknesses, your result should look like the Lambertian shown in the course. Approximate the generation rate by a constant average through $G = j_{ph}/d$.
Task: Create a table of cell thickness d vs. G for your colleague working on b).

b) Find a relation between the generation rate G and the injection level Δn.
Assume you receive a table in which one column contains G. Using p-type material that is doped with $N_A = 10^{16}\ \mathrm{cm}^{-3}$, consult Richter, PRB (2012) for a parametrisation of radiative and Auger recombination mechanisms, e.g. their eq. (22). Noting that the generation rate is given by $G = \Delta n/\tau(\Delta n)$ and thus essentially a function of Δn, define a procedure to find the inverse function $\Delta n = \Delta n(G)$. To do so analytically, find the dominating recombination process and use a convenient approximation (hint: radiative and Auger processes transit from a constant value at low Δn into branches proportional to Δn^{-1} and Δn^{-2} at high Δn, respectively.). Alternatively, if you prefer working with the general description, you may define a look-up table.
Task: Extend the table with a column that contains $\Delta n(G)$ for your colleague working on c).

c) Find the limiting efficiency.
Assume you receive a table in which one column contains Δn. Find the implied V_{oc} which is equal to the quasi-Fermi level splitting $iV_{oc} = \Delta_{QFL} = kT/q \ln\left(np/n_i^2\right)$. Use the relations $n = n_0 + \Delta n = n_i^2/N_A + \Delta n$ and $p = p_0 + \Delta n = N_A + \Delta n$ with the doping concentration N_A given in part b). Next, consult Green, Solar Energy (1982) tht relates the fill factor to the V_{oc}.(in your case iV_{oc}) In line with finding an upper limit for the efficiency, you may assume zero series-resistance and infinite parallel-resistance.
Task: Extend the table by three more columns, containing iV_{oc}, the fill factor, and finally the projection of the efficiency given by $\eta = j_{ph} \cdot iV_{oc} \cdot FF_0$.

All: Plot the efficiency η vs. the device thickness d and discuss the result.