Exercise 3.1: Models for the permittivity of metals (5-7 min)

For metals, the permittivity is generally a complex quantity ($\epsilon_M = \epsilon' + i\epsilon''$). A very simple model can be obtained from the fourth Maxwell-equation, the modified Ampere-law and assuming that the relation between $\vec{D}$ and $\vec{E}$ is described by the permittivity ϵ:

$$\nabla \times \vec{H} = \vec{j} + \epsilon\epsilon_0 \cdot \partial\vec{E}/\partial t$$

a) Get rid of the time-derivative by assuming a harmonic time dependence of the form $\exp(-i\omega t)$ and express current density with the conductivity by $\vec{j} = \sigma\vec{E}$. Identify the following relations:

$$\epsilon' = \epsilon$$

$$\epsilon'' = \frac{\sigma}{\omega\epsilon_0}$$

Drude described the conductivity in metals by free electrons that can follow variations of the electric field only up to a certain limiting frequency. Thus, the permittivity is determined by a relaxation time τ and the plasma frequency ω_p.

$$\epsilon_M = 1 - \frac{{\omega_p}^2}{\omega(\omega + i/\tau)}$$

The plasma frequency depends on the density of conduction-electrons N, their effective mass is m^* and their charge e by means of $\omega_p = \sqrt{e^2N/m^*\epsilon_0}$.

b) Separate ϵ_M into real and imaginary parts and compare the high- and low-frequency limits of your result for the imaginary part with the result of the quasi-static case.
c) Find a data for a typical metal such as silver or aluminium, plot on a convenient scale and identify the transition between the models.

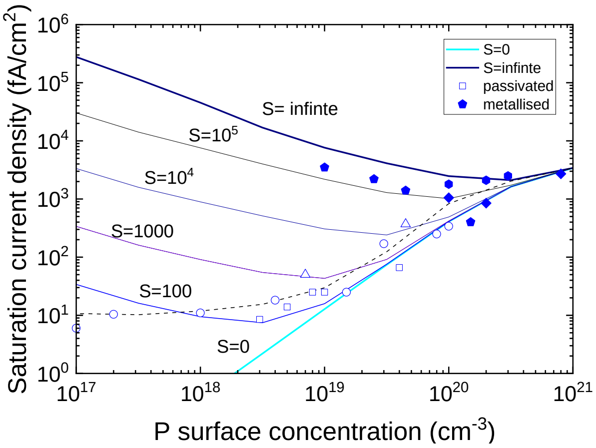
Task: Show only the key points of the derivation, minimise the use of formulae. Focus on the discussion of the data.

Exercise 3.2: 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 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.



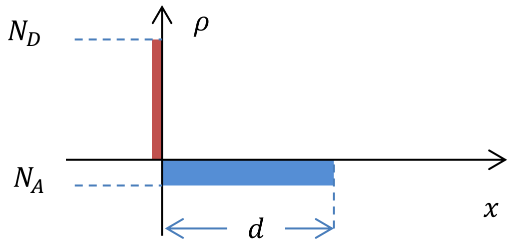
c) Assume a *passivated emitter* with reduced surface concentration of $N_D = 10^{19}\ \mathrm{cm}^{-3}$. Project the j_0 by using an area weighted sum of $j_{0,met}$ and $j_{0,pass}$, assuming that the silver fingers cover an area of 10%.

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 3.3: Schottky barrier (5-7 min)

The front contact in hetero-junction solar-cells is established between a highly n-doped ITO layer and a p-doped layer. In the depletion approximation, we assume that mobile charges recombine across the interface, leaving behind ionized cores. The depletion-regions are thus charged positively in the n-type ITO and negatively in the p-doped layer.



In the p-doped layer, we assume that the depletion zone extends over a width d that is less than the film thickness. Throughout this depleted region, we may assume a negative charge density equal to the acceptor concentration N_A. Since the ITO is highly doped, its depletion zone is very narrow and can be treated like a surface charge. The result is a one-sided p-n junction, similar to a Schottky-junction.

a) Applying the 1D Poission-equation $d^2\phi/\,dx^2 = qN_A/\epsilon\epsilon_0$, you can find a relation for the electric field E by recognizing that $d\Phi/dx = -E$. Integrate once and evaluate the boundary condition that the field vanishes at the edge of the depletion zone ($E(d) = 0$).
b) Find the electrostatic potential by carrying out a second integration. Determine the width of the depletion layer for a known height of the potential barrier V_b.
c) Find experimental data for barrier heights between metals and silicon, e.g. Schroder, TED (1984). Compare with theoretical values based on the work function.

Task: Show only the key results of the derivation with a minimum of formulae