SOLUTION SERIES 12

Exercise 1: Laser doped solar cells

Read the article *S.J. Eisele et al., 18.9 % efficient full area laser doped silicon solar cell, Appl. Phys. Lett. 95, 133501, 2009*

a) What are the advantages of laser doping (LD)?

Solution:

The main advantages of this technique are first the possibility to dope selectively semiconductors and second to dope at room temperature (heating of a wafer at high temperature is not required unlike in a diffusion process). It is also a one side process and thus you do not form an emitter on the two sides of your wafer as in a POCl3 diffusion used in the standard cell processing .

b) What was the main drawback of this method and what is the main claim of improvement shown by this article?

Solution: For previous LD techniques, the process had to be done under vacuum or in an inert atmosphere making this technique not suitable for low cost fabrication of a p-n junction. Here, on the contrary, the authors developed a process working at ambient atmosphere and without the need for clean room conditions.

c) Describe the whole process for the fabrication of the p-n junction presented in this paper.

Solution: On a p-type wafer, a 60 nm thick pure layer of phosphorous is deposited by sputtering (a pyhsical vapor deposition low-cost process). Then, a green-light laser pulse is used to melt the silicon up to a depth of around 1 µm. When the silicon cools down, it growths epitaxially incorporating the phosphorous n dopant, creating the p-n junction. Eventually, the wafer is cleaned to remove the remaining phosphorous residuals.

d) Do they passivate the wafer of their record cell made with LD?If yes, how and why?

Solution: They use an oxide layer of SiO_2 to passivate the front and rear surface, in order to reduce the surface recombination velocity of both surfaces.

e) Do they use an antireflection coating on their record cell made with LD? If yes, which kind?

Solution: They use an antireflection coating made of two layers: a 35 nm of ZnS covered by a 100 nm of MgF_2. This two layer coating leads, as you can see on Fig. 2 of the paper, to an antireflection effect over a wider wavelength range compared to an antireflection coating made of only one single layer.

f) How do they create the back metallic contacts of their record cell made with LD?

Solution: The contacts are made with Al through the holes on the rear SiO_2 layer. With this method, the passivation layer is still effective on most of the back surface, i.e. everywhere except underneath the contacts.This helps to keep a high V_{oc}

g) Compare the three cells (A,B,C) presented in this paper and comment on their differences regarding their performances.

Solution: V_{oc}: The cell A is passivated on the front side by a SiN layer, which provides in this experiment a poorer passivation quality than the SiO_2 layer used for the two other cells. Therefore cell B and C have a higher V_{oc} than cell A.
Cell C has a passivation layer on the rear surface whereas cell B has none. Due to the higher surface recombination velocity, the saturation current is higher, leading to a lower open-circuit voltage in cell B compared to cell C.

J_{sc}: Cells B and C have a double antireflective layer whereas cell A has only one single layer. Therefore more light is coupled into cells B and C leading to a higher generated photocurrent (we can see it in the reflection measurements).

To conclude, cell C is the best cell, not only because of the good passivation at the front and back surface, but also because of a better light coupling into the absorber layer.

h) How do they verify the potential of their approach?

Solution: They measure the effective minority-carrier lifetime by a photoconductive decay method to access the emitter saturation current density and then to extract theoretically the maximum achievable V_{oc}.

i) In Fig. 3, why does J_{0e} increase when the sheet resistance decreases?

Solution: The sheet resistance R_s increases according to:

$$R_s = \frac{\rho}{t} = \frac{1}{\sigma t} = \frac{1}{e(n\mu_e + p\mu_h)t} \tag{1}$$

where t is the layer thickness, ρ the resistivity, σ the conductivity, e the elementary charge, n and p are the electron and hole concentration where $n = n_0 + \Delta n = N_D + \Delta n$ (n_0 is the equilibrium electron concentration, which is equal at 25 °C to N_D the donor concentration, Δn is the electron concentration out of equilibrium (under illumination for instance). For measures in the dark and no bias, $n \approx N_D$ at 25 °C), μ_e (μ_h) the electron (hole) mobility.
Thus, as the carrier concentration n in the n-type emitter increases (via doping), R_s decreases according to Equ. 1. The emitter saturation current density is given by (since the emitter is n-type):

$$J_{0e} = \frac{eD_p n_i^2}{N_D Lp} G_F \tag{2}$$

where D_p is the hole diffusion coefficient, n_i the intrinsic carrier concentration, N_D donor concentration, L_p the hole diffusion length and G_F the geometric factor (indeed, since the emitter is n-type, we consider the minority carriers (holes) parameters, with a concentration of n_i^2/N_D).
At first sight, according to Eq. 2, J_{0e} should follow R_s behaviour (decreases when N_D increases, and vice versa), so should increase when R_s increases.
However, we observe here the opposite trend. The explanation comes from the high doping

concentration in the emitter. At high doping concentrations, L_p and n_i^2 begins to depend on N_D, since Auger recombination will limit strongly the diffusion length in the emitter and band gap narrowing will lead to a higher n_i^2 values, so J_{0e} will decrease when R_s increases. In this paper, we can then deduce that Auger recombination governs J_{0e}, as J_{0e} versus R_s follows the second trend.

j) Do they use a selective (here, means locally doped) emitter ? Do they discuss the area of metallized fraction?

Solution: A selective emitter consists of a locally highly doped n_{++} region underneath the front contacts to achieve a better contact with the metal (lower contact resistance) and to lower the recombination rate at the contacts by a doping induced field-effect. In the cell described in this paper, the emitter doping is uniform. As a consequence, they do not use a selective emitter.

Nevertheless, for their best cell, a good FF is obtained while maintaining a good V_{oc} of 677 mV. This can be explained by three facts. First, the fingers at the frontside are evaporated. Evaporation is less critical regarding the diffusion of metallic atoms into the junction (this diffusion severely impact $V_{\mathrm{oc}}$and FF) than a firing of the contacts (like in standard Al-BSF cells process). In addition, they have a low doping level in the emitter (relatively high sheet resistance), so not too strong Auger recombination, and a passivating SiO_2 layer, leading to a lower surface recombination velocity. Futhermore, the contact area between the metal and the semiconductor plays a crucial role for J_{0e}, as this interface is highly recombinative. At the front, they do not precise the metalized fraction. At the back, on cells A and C, rear local contacts are processed, leading to a low fraction of metal-semiconductor contact. This also contributes to a low J_{0e}. Hence, J_{0e} is low and the V_{oc} is satisfactory.

k) Give all the steps to process such a solar cell.

Solution:

1	Wafer sawing/wafer etching (isotropiic) to remove the part damaged by the wafer sawing
2	Etching (anisotropic) of the wafer to create pyramids
3	Deposition of the phosphorous layer/creation of the pn junction with the laser
4	Cleaning of the phosphorous layer/etching away the phosphorous residues
5	Photolithography for the contacts
6	Deposition of the SiO_2 layer to passivate surfaces
7	Deposition of the antireflection layers
8	Lift-off
9	Cleaning
10	Deposition of the contacts