SOLUTION SERIES 11

Exercise 1: Improvement of the V_{oc} with the back Surface Field (BSF)

Let's consider a standard Al-BSF solar cell whose base is p-type. As seen in the lecture, to fabricate such cells, different processed are required. To create the front emitter (and then the p-n junction), phosphorus (to create n-type doping) is diffused at the front of the p-type cristalline silicon. The emitter and base doping are $\approx 10^{20}\,\text{cm}^{-3}$ and $\approx 10^{16}\,\text{cm}^{-3}$ respectively. For the back-contact, a film of an Al paste is screen-printed. If the paste is only dried (heating around 210 °C during 20 min) after this step, the resulting contact creates a very bad surface recombination velocity near to $10^{7}\,\text{cm}\,\text{s}^{-1}$ leading to a poor V_{oc}since the temperature is not high enough to activate the Al diffusion into Si at the back side.

To overcome this issue, the firing-through process (heating around 900°C during 2 min) leads to the insertion of Al atoms into the silicon, creating a cristallised Al-Si alloy at the back side which creates a p-type doped region, called Back Surface Field (BSF). The resulting p+ region provokes the apparition of an electrical field which repels the minority carriers (electrons) from the surface, which decreases the surface recombination velocity (less minority carriers available, so less recombination possible). The doping level (= Al concentration) of this latter region is called N_S.

Fig. 1 shows the V_{oc} dependency with the BSF depth for different N_S and for a surface recombination velocity of $10^{6}\,\text{cm}\,\text{s}^{-1}$.

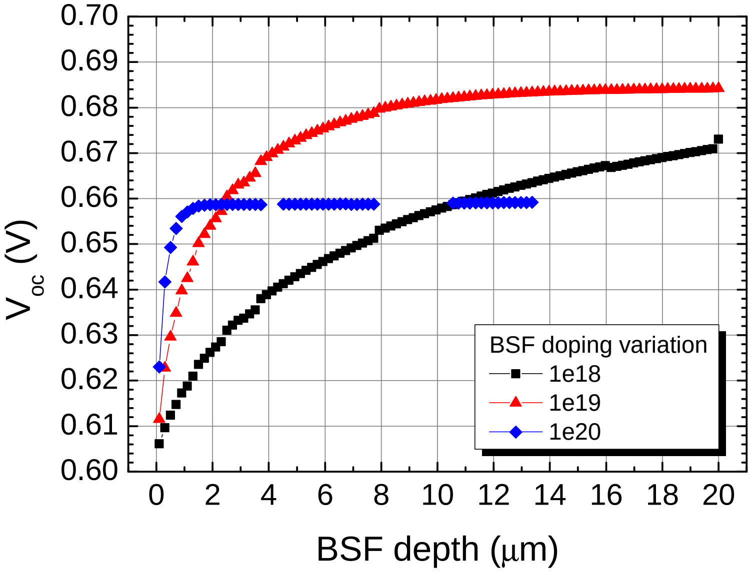

Figure 1: V_{oc} versus BSF depth for different BSF doping levels. From PC1D simulations

a) Explain the dependency of the V_{oc} with the BSF depth.

Solution:

As can be seen in Fig. 1, for thin BSF, all $V_{\mathrm{oc}}$are increasing with BSF thickness, up to a certain value (depending on BSF doping), then remain constant. These regions, where $V_{\mathrm{oc}}$are increasing and don't reach their maximum, expand on different thicknesses according to the different doping level of the BSF (e.g., <2 µm for a doping of $10^{20}\,\mathrm{cm}^{-3}$, or >10 µm for a BSF doping of $10^{19}\,\mathrm{cm}^{-3}$). They correspond to thicknesses smaller than the diffusion length of minority carriers in the BSF, meaning that these carriers could still cross the BSF and reach the rear surface to recombine with holes. In that case, the BSF is not efficient enough to repel all the minority carriers and does not lead to a significant improvement of the V_{oc}(compared with no BSF). On the contrary, when the BSF is thick enough (=thicker than its own diffusion length), minority carriers cannot reach the back surface and are efficiently repelled. V_{oc}'s reach their maximum and remain constant as minority carriers do not see the back surface anymore (once the BSF is wider than its diffusion length, widen it even more won't change the recombination at the back surface, so won't change the V_{oc}neither).

In terms of band diagram, changing the doping of the BSF changes the height of the barrier (strength of the electric field) while changing the width of the BSF only changes the width of the energy plateau after the barrier, which increases with BSF width. When wider than the diffusion length, this plateau enables minority carriers which crossed the barrier to return to the bulk without reaching the rear surface. For a thin BSF (small plateau width), minority carriers which cross the barrier immediately reach the rear surface where they recombine. Note that this phenomenon is even more true for lightly doped BSF as the barrier is lower and the diffusion length is longer.

b) Explain the dependency of the V_{oc} with the BSF doping level.

Solution:

For the doping level of the BSF, we see that an Al concentration of $10^{20}\,\mathrm{cm}^{-3}$ leads to lower values of V_{oc} than a $10^{19}\,\mathrm{cm}^{-3}$ BSF. This phenomenon is explained by the Auger recombination occurring at high doping levels which leads directly to a V_{oc} decay. In the opposite case, a too lightly doped BSF does not create a sufficient electrical field to repel the minority carriers and does not lead to a significant improvement of the V_{oc}.

The BSF doping level is then a trade-off between these two previous phenomena. We can also note that if good passivations are achieved with thin BSF for the high doping case, the low doping created with the Al paste requires to use thick BSF and thus leads to a high paste consumption.

Exercise 2: Diffusion technologies for p-n junction creation

Two processes are mainly used nowadays in the semiconductor industry for the creation of p-n junctions:

- The ion implantation. This technique was the first used for earliest solar cells and gives a good homogeneity and an accurate control of the junction depth. Moreover, this technique allows the possibility to create more doped regions in the purpose to realize selective emitter solar cells. Nevertheless, if this technique is massively used by the CMOS industry, it plays only a minor role in the solar cell industry nowadays.
- The thermal diffusion of dopants. For n-type doping, a gas containing phosphorus ($POCl_3$) is used with oxygen to create a doped silicon oxide at the surface of the wafer. Then, a thermal diffusion is carried out to transfer the dopant into the silicon. You can find more information about this process on the website of the CMI (`http://cmi.epfl.ch/thinfilms/Tube_1-4.php`).

The diffusion process follows the second Fick law:

$$\frac{\partial N(x,t)}{\partial t} = D\frac{\partial^2 N(x,t)}{\partial x^2} \tag{1}$$

Where $N(x,t)$ is the density of dopants in function of the position and of the time. The dependency of $D(T)$ with the temperature explains why the diffusion process is carried out at high temperature. Here is two ways to solve the latter differential partial equation (DPE) :

- With a constant surface density of dopants N_S if we suppose an infinite source of dopants. The solution of the DPE is then :

  $$N(x,t) = N_S \cdot erfc(\frac{x}{2\sqrt{Dt}}) \tag{2}$$

  Where the *erfc* function is called the complementary error function distribution. This case is shown by Fig.2.

- With a given number of dopants if we consider a finite source with a surface concentration Q (cm^{-2}) .

  The solution of the DPE is then :

  $$N(x,t) = \frac{Q}{\sqrt{\pi Dt}} exp\left\{-\left(\frac{x}{2\sqrt{Dt}}\right)^2\right\} \tag{3}$$

  This case is shown by Fig.3

a) Prove that the latter $N(x,t)$ for the finite source case is a solution of the Fick law.

Solution: The proof is done simply by replacing the solution in the DPE:

$$\frac{\partial N(x,t)}{\partial t} = D\frac{\partial^2 N(x,t)}{\partial x^2} \tag{4}$$

$$\frac{\partial}{\partial t}\frac{Q}{\sqrt{\pi Dt}}exp\left\{-\left(\frac{x}{2\sqrt{Dt}}\right)^2\right\} = D\frac{\partial^2}{\partial x^2}\frac{Q}{\sqrt{\pi Dt}}exp\left\{-\left(\frac{x}{2\sqrt{Dt}}\right)^2\right\} \tag{5}$$

For the temporal part:

$$\begin{aligned}\frac{\partial}{\partial t}\frac{Q}{\sqrt{\pi Dt}}exp\left\{-\left(\frac{x}{2\sqrt{Dt}}\right)^2\right\} &= \frac{-Q}{2\sqrt{\pi D}}t^{\frac{-3}{2}}exp\left\{-\left(\frac{x}{2\sqrt{Dt}}\right)^2\right\} \\ &\quad +\frac{Q}{\sqrt{\pi Dt}}\frac{x^2}{4Dt^2}exp\left\{-\left(\frac{x}{2\sqrt{Dt}}\right)^2\right\} \\ &= \frac{-Q}{2\sqrt{\pi D}}t^{\frac{-3}{2}}exp\left\{-\left(\frac{x}{2\sqrt{Dt}}\right)^2\right\} \\ &\quad +\frac{Q}{\sqrt{\pi D}}\frac{x^2}{4Dt}t^{\frac{-3}{2}}exp\left\{-\left(\frac{x}{2\sqrt{Dt}}\right)^2\right\} \\ &= \left[\frac{-1}{2}+\frac{x^2}{4Dt}\right]\frac{Q}{\sqrt{\pi D}}t^{\frac{-3}{2}}exp\left\{-\left(\frac{x}{2\sqrt{Dt}}\right)^2\right\} \end{aligned} \tag{6}$$

For the spatial part:

$$D\frac{\partial^2}{\partial x^2}\frac{Q}{\sqrt{\pi Dt}}exp\left\{-\left(\frac{x}{2\sqrt{Dt}}\right)^2\right\} = D\frac{Q}{\sqrt{\pi Dt}}\frac{\partial}{\partial x}\frac{-2x}{4Dt}\cdot exp\left\{-\left(\frac{x}{2\sqrt{Dt}}\right)^2\right\} \tag{7}$$

$$= D\frac{Q}{\sqrt{\pi Dt}}\left[\frac{-2}{4Dt}\cdot exp\left\{-\left(\frac{x}{2\sqrt{Dt}}\right)^2\right\} + \frac{-2x}{4Dt}\cdot\frac{-2x}{4Dt}\cdot exp\left\{-\left(\frac{x}{2\sqrt{Dt}}\right)^2\right\}\right] \tag{8}$$

$$= D\frac{Q}{\sqrt{\pi Dt}}exp\left\{-\left(\frac{x}{2\sqrt{Dt}}\right)^2\right\}\left[\frac{-2}{4Dt}\cdot + \frac{-2x}{4Dt}\cdot\frac{-2x}{4Dt}\right] \tag{9}$$

$$= D\frac{Q}{\sqrt{\pi D}}t^{-\frac{3}{2}}exp\left\{-\left(\frac{x}{2\sqrt{Dt}}\right)^2\right\}\left[\frac{-2}{4D}\cdot + \frac{-2x}{4Dt}\cdot\frac{-2x}{4D}\right] \tag{10}$$

$$= D\frac{Q}{\sqrt{\pi D}}t^{-\frac{3}{2}}exp\left\{-\left(\frac{x}{2\sqrt{Dt}}\right)^2\right\}\left[\frac{-2}{4D}\cdot + \frac{x^2}{4D^2t}\right] \tag{11}$$

$$= \frac{Q}{\sqrt{\pi D}}t^{-\frac{3}{2}}exp\left\{-\left(\frac{x}{2\sqrt{Dt}}\right)^2\right\}\left[\frac{-1}{2}\cdot + \frac{x^2}{4Dt}\right] \tag{12}$$

Since the temporal and the spatial part are the same, the latter expression of $N(x,t)$ is a solution of the DPE.

b) Explain Fig.3

Solution: Since this graphic is for the finite source case, we can evaluate $N(x,t)$ for the surface. We obtain the surface concentration which is given by:

$$N_S = \frac{Q}{\sqrt{\pi D t}} \tag{13}$$

We see that N_S decreases in function of the time as it can be seen on Fig.3. This can be explained by the finite source ; in function of the time, the source contains less dopants and then the surface concentration decreases.

We can also see that increasing the diffusion time leads to a deeper junction. Indeed, due to the diffusive process, dopants need times to diffuse and then increasing the diffusion time allows the dopants to go deeper into the silicon.

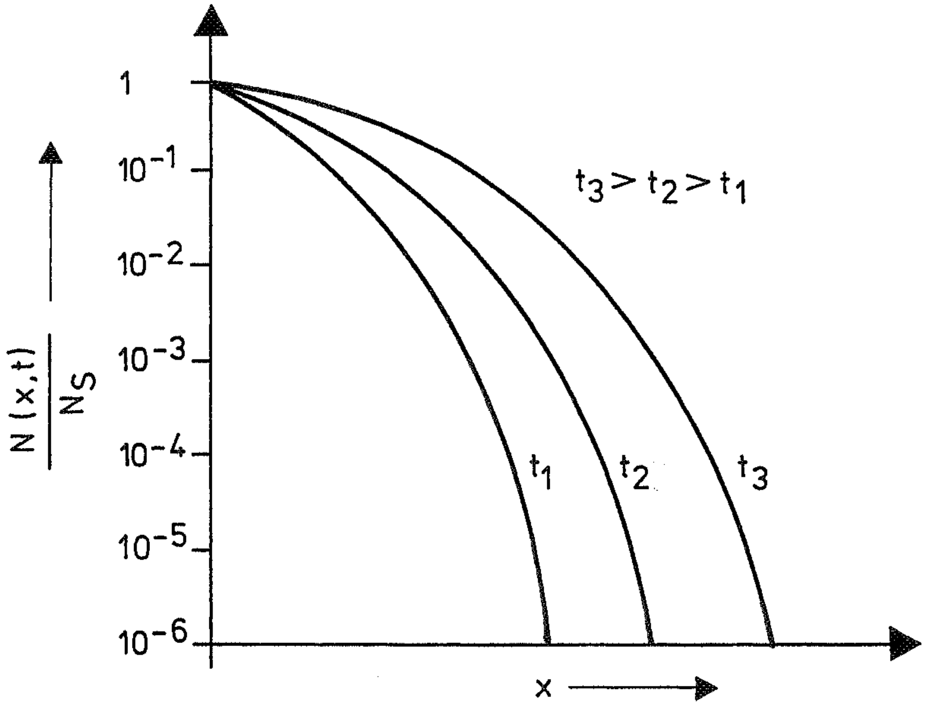

Figure 2: Diffusion case with an infinite source of dopants. From "Crystalline Silicon Solar Cells" A. Götzberger

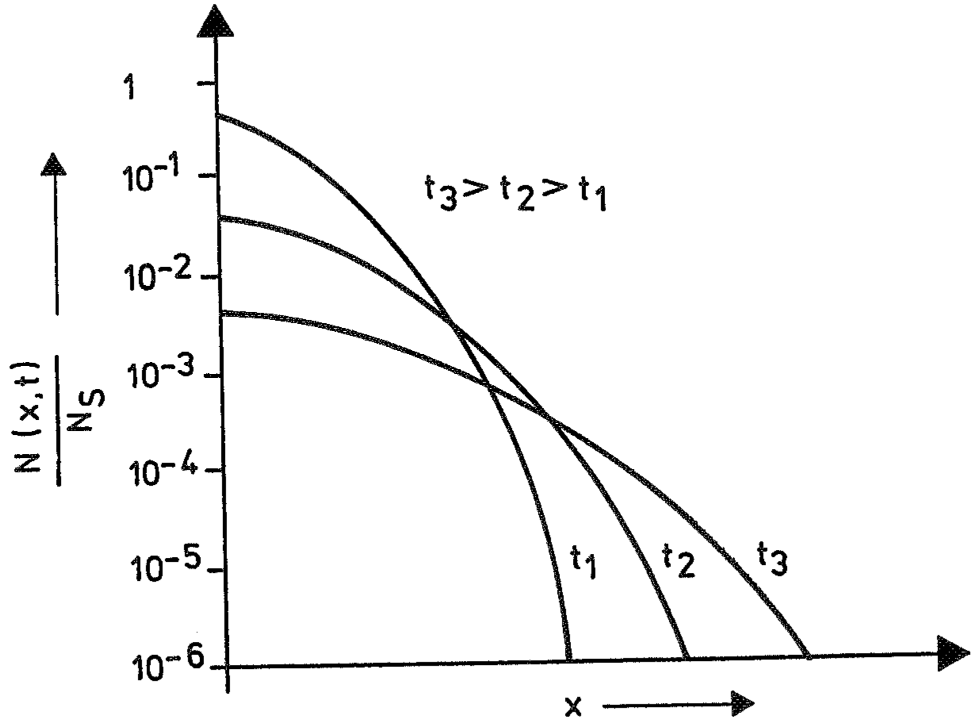

Figure 3: Diffusion case with a finite source of dopants. From "Crystalline Silicon Solar Cells" A. Goetzberger