# CONDUCTION PROCESSES IN SILICON SOLAR CELLS

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## ABSTRACT

Dark I-V experiments have been performed on directional solidification (DS), Czochralsky (CZ) and cold crucible casting (CCC) silicon solar cells. Series and shunt resistances, ideality factors and saturation currents have been determined. However the usual equations (recombination and diffusion current) cannot fit some cells maybe because they are too approximated or because other mechanisms are present. The aim of this work is to explain the mechanisms occurring in these cells and to correlate them with the device characteristics. We show that for some solar cells we must add to the usual two exponential model (diffusion and recombination) trap assisted tunneling current and field assisted recombination. The influence of the material on these currents has also been investigated.

## INTRODUCTION

The fill factor is very important for solar cells because it characterizes solar cells at maximum power point. That is why the knowledge of the mechanisms that could decrease or increase this parameter is primordial. The fill factor is influenced by series resistance $R_s$, shunt resistance $R_{sh}$, dark currents and open circuit voltage. The last parameter is determined by I-V curve under illumination. The other ones are calculated from dark I-V measurements. However the usual equations (recombination and diffusion current) cannot fit some cells, maybe because they are too approximated or because other mechanisms are present. The aim of this work is to explain the mechanisms occurring in these cells. In the first part, we recall standard equations used to model solar cells and we also present other processes which could explain high ideality factors. In the second part, we describe the experimental setup and the procedure to get the junction parameters. In the last part, we present the results and discuss them.

## POSSIBLE MECHANISMS IN SOLAR CELLS UNDER DARK CONDITIONS

Diffusion and recombination currents are the commonly used mechanisms to explain dark I-V curves. Diffusion current is characterized by an ideality factor equal to one and it varies versus forward bias V and temperature T as [1]:

$$I_F = I_s\left[\exp\left(\frac{qV}{kT}\right)-1\right] \quad \text{with :} \quad I_s \propto T^3 \exp\left(-\frac{E_g(T)}{kT}\right)$$

where Is is the saturation current and Eg the gap of the material.

Recombination current in the space charge region (SCR) varies as [1]:

$$I_F = I_s\left[\exp\left(\frac{qV}{nkT}\right)-1\right] \quad \text{with :} \quad I_s \propto T^{3/2} \exp\left(-\frac{E_g(T)}{2kT}\right)$$

where n is the ideality factor.

For this mechanism, the ideality factor n is between 1 and 2. However, some authors have demonstrated that deviations can occur in asymmetric junctions [2,3].

The Poole-Frenkel effect [4] or in other terms recombination current assisted by field is due to the lowering of the potential barrier of traps under high fields , increasing the recombination current. This current is proportional to :

$$I_{P-F} \propto \exp\left[\frac{q\beta^{1/2}E^{1/2}}{2kT}\right] n_i W^* \left[\exp\left(\frac{qV}{2kT}\right)-1\right]$$

$$\propto T^{3/2} \exp\left[\frac{-E_g(T)+q\beta^{1/2}E^{1/2}}{2kT}\right]\left[\exp\left(\frac{qV}{2kT}\right)-1\right]$$

where $n_i$ is the intrinsic concentration, $\beta=q/\pi\varepsilon$, $\varepsilon$ is the dielectric constant, W* the effective space charge region width and E is the electric field at the recombinaison center. This current can lead to ideality factors higher than two.

As pointed out by Hovel [5], trap assisted tunneling is very probable in solar cells with defects and highly doped emitters. To model this mechanism, we use the analytical formula given by [6,11]:

$$I_T \propto \exp(-AW)\exp(BV) \propto \exp(-\alpha E_g(T))$$

where A and B depend on the doping properties of the junction. This current can also lead to ideality factors greater than two.

From the above equations we conclude that only the diffusion process can give an ideality factor equal to one. Standard recombination in the SCR has an ideality factor between one and two in the usual approximations. Trap assisted tunneling current and Poole-Frenkel effects lead to ideality factors larger than two. At ambient temperature these last mechanisms cannot be determined. It requires studies versus temperature. Moreover this is very useful to confirm the presence of diffusion and / or recombination process.



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If trap assisted tunneling current prevails, the temperature dependence is lower than for the recombination [7] and the exponential factor B is fairly constant versus temperature. In the case of Poole-Frenkel mechanism, the trap barrier lowering decreases with the forward voltage, and can yield to an ideality factor that seems to have increased with voltage.

## EXPERIMENTAL SETUP

Czochralsky (CZ), Directional solidification (DS) and cold crucible casting (CCC) silicon solar cells have been studied. In order to explain conduction mechanisms, we have perform experiments versus temperature for two 2*2 $cm^2$ DS solar cells and one CZ solar cell. We have also compared solar cells made with different materials at ambient temperature. The I-V apparatus covers the $10^{-7}$ to 5A range. For temperature dependent manipulations, the cell is inside a cryostat regulated from 77K to 400K, with an absolute accuracy of 0.1K.

To extract the parameters, we consider that the equivalent electrical network contains a rectification (two exponentials) plus a series (Rs) and a shunt resistance (Rsh). The total forward current formula is given by :

$$I_{dark} = I_{s1} \exp(\alpha_1(V - IR_s)) + I_{s2} \exp(\alpha_2(V - IR_s)) + \frac{V - IR_s}{R_{sh}}$$

The determination of the parameters is done with the following sequences :

* calculation of $I_{s1}$, $\alpha_1$, $R_s$ for high voltages using a new method especially adapted for low series resistance to be submitted to publication. For this calculation, we consider that in our range of current, crowding effects and high injection phenomena are negligible and the first exponential predominates ;

* subtraction of this exponential from the rest of the curve and determination of the other exponential (using the least square method) ;

* if $\left(\frac{dI}{dV}\right)$ over the voltage range used to determine $\alpha_2$ and $I_{s2}$ is big as compared to $R_{sh}^{-1}$, we have accuracy on $\alpha_2$ and $I_{s2}$ and we determine $R_{sh}$ using the following relation :

$$R_{sh} = \left[\left(\frac{dI}{dV}\right)_{V\to 0} - I_{s1}\alpha_1 - I_{s2}\alpha_2\right]^{-1}$$

otherwise we use a least square fit at the low voltage range to find $R_{sh}$, $I_{s2}$ and $\alpha_2$.

## RESULTS

### Experiments versus temperature

The curves versus temperature (from 90 to 323K with a step of 20K approximately) obtained with the two DS solar cells are shown in figure 1. Their behavior versus temperature are quite similar : for high voltages, the exponential varies rapidly versus temperature and for low voltages, the variation versus temperature of the exponential is lower especially for the second solar cell.

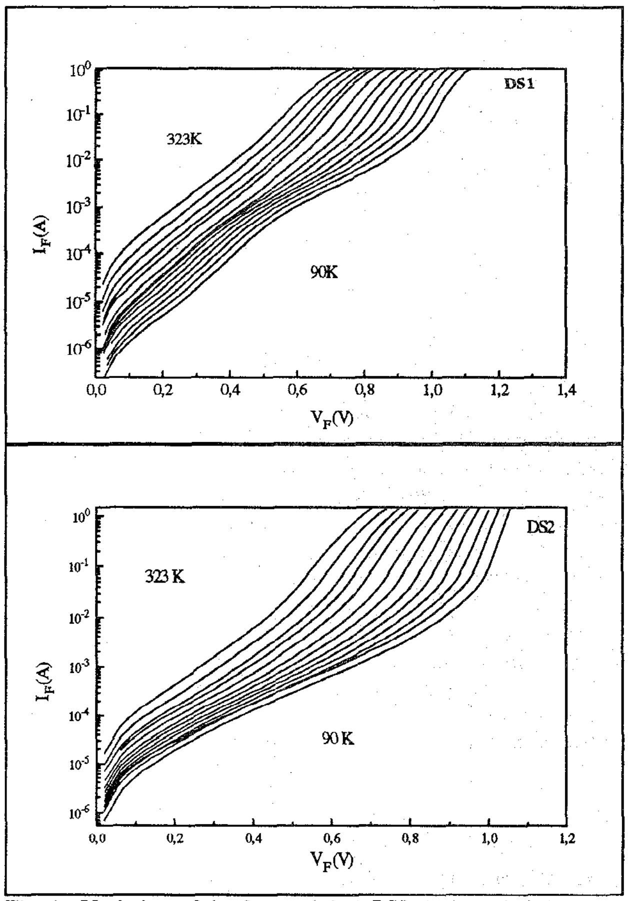


Fig .1 : Variation of the forward dark I-V characteristics versus temperature of the DS solar cells.

For large forward biases, the curves show an exponential behavior with an ideality factor equal to 1.5 at ambient temperature and about 2 at 90 K. The Arrhenius plots of the saturation current (see fig. 2) for the two cells give respectively an activation energy of 0.51eV and 0.55eV which is nearly half the gap (Eg=1.06 taking into account band-gap narrowing effects [8]). Consequently the conduction process is recombination.

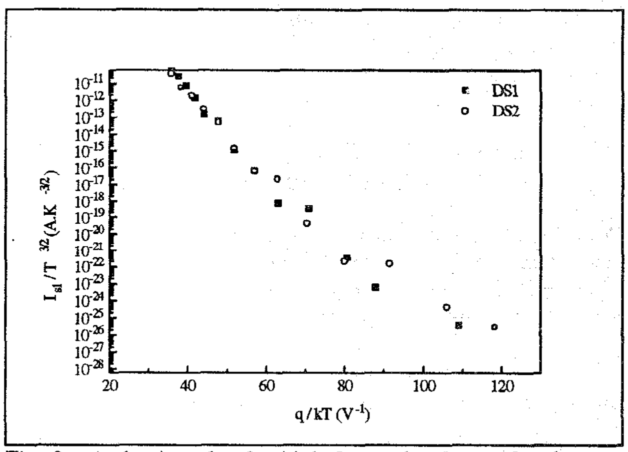


Fig. 2 : Arrhenius plot for high forward voltages for the two DS solar cells.

For low voltages, we can also see an exponential behavior with ideality factors much over 2. Three explanations are possible :

- the usual approximations made in formulas [2,3] for the recombination current are not well adapted,
- trap assisted tunneling current occurs,
- a Poole-Frenkel effect increases the recombination current.

Two facts show that the current can be due to a trap assisted tunneling current : the variation of the coefficient of the exponential is low and the current varies exponentially with the gap (see fig. 3). However, for the cell DS1, this conclusion is not as evident as for DS2 because for low temperatures and low voltages, the slope of the curve varies. Therefore a Poole-Frenkel effect is not excluded.

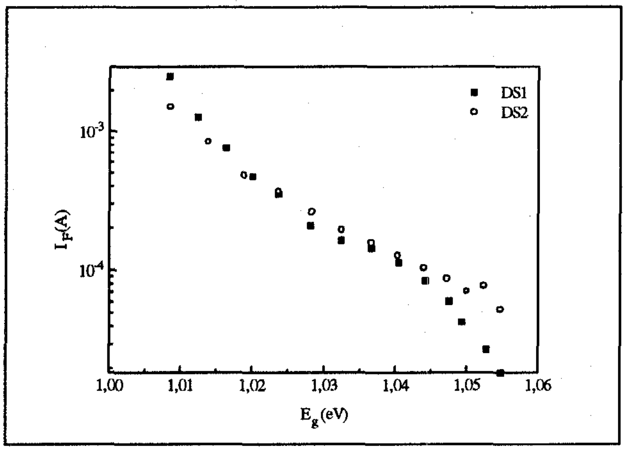


Fig. 3 : Current versus variation of band gap energy with temperature [1] for $V_F$=0.3V. Other voltages, for example 0.2V, give the same behavior.

The curves versus temperature of the CZ cell are shown in figure 4.

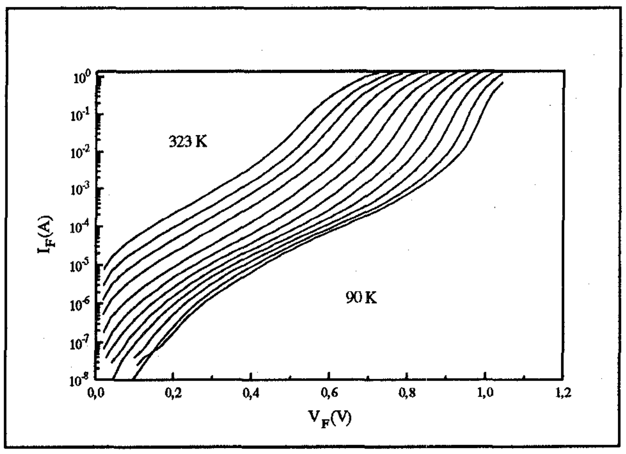


Fig. 4 : Variation of the forward characteristic of the CZ solar cell versus temperature.

For the exponential at high voltages, this last sample has an ideality factor approximately equal to 1.2 and the Arrhenius plot gives an activation energy of 0.9 eV for the diffusion process. At low voltages, the variation of the current with temperature is more important than for DS solar cells except at very low temperatures. Moreover, for low temperatures, the slope of the curves is not constant at low voltages and the ideality factor increases. This could correspond to possible Poole-Frenkel effect or trap assisted tunneling.

The variation of the series resistance versus temperature is linear as could be seen on figure 5. Such a smooth behavior shows the accuracy of our method for the determination of series resistance.

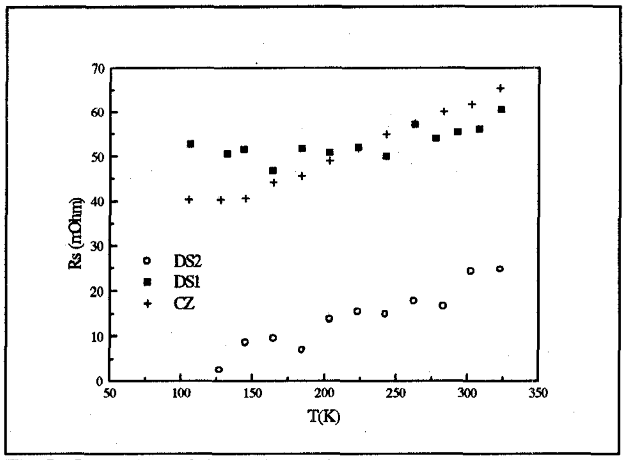


Fig 5 : Variation of the series resistance versus temperature.

The variation of the shunt resistance versus temperature is exponential (see fig.6).

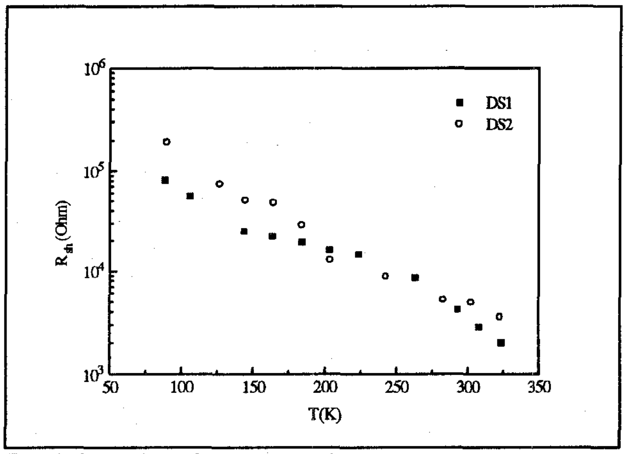


Fig. 6 : Variation of the shunt resistance versus temperature.

**Comparison of solar cells made with different materials**

A comparison between 10*10 $cm^2$ solar cells fabricated by the same process with CZ, DS and CCC is shown near ambient temperature (15°C) in figure 7. If we consider the quality of the material, CZ can be classified as the best one followed by CCC1 and DS, and finally CCC2 is the worse.

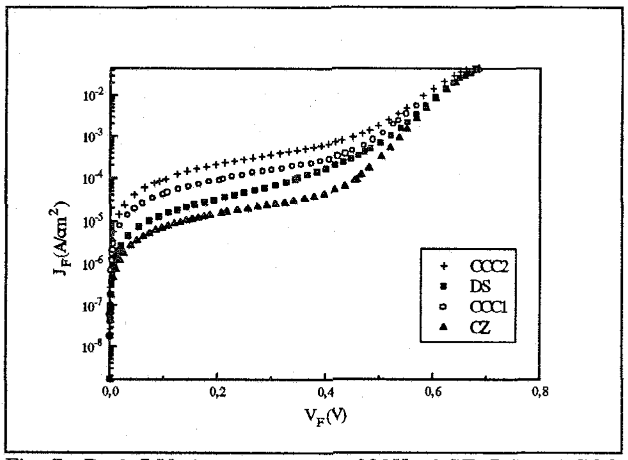

Fig. 7 : Dark I-V characteristics at 293K of CZ, DS and CCC solar cells.

The calculated parameters of these solar cells are given in table 1.

| Material | CCC1 | CCC2 | DS | CZ |
|---|---|---|---|---|
| $\alpha_1$ ($V^{-1}$) | 29,8 | 24,4 | 30 | 34,7 |
| $n_1$ | 1,3 | 1,58 | 1,3 | 1,1 |
| $J_{s1}$ ($A/cm^2$) | $2,87.10^{-10}$ | $8.10^{-9}$ | $1,44.10^{-10}$ | $9,3.10^{-12}$ |
| $\alpha_2$ ($V^{-1}$) | 8 | 9 | 11 | 7 |
| $n_2$ | 4.7 | 4 | 3.4 | 5.5 |
| $J_{s2}$ ($A/cm^2$) | $2.10^{-6}$ | $6.10^{-6}$ | $1.10^{-6}$ | $1.10^{-6}$ |
| $R_s$ ($Ohm.cm^2$) | 0,9 | 0,6 | 0,6 | 0,8 |
| $R_{sh}$ ($Ohm.cm^2$) | 2300 | 1100 | 9000 | 15000 |

Table 1 : Values of the parameters of the solar cells.

The high values of $J_{s2}$ and $n_2$ are due to the low value of $R_{sh}$ which is the predominant mechanism at low voltages and makes impossible the determination of the second exponential with precision.

## DISCUSSION

In the first part of this study, we have shown that we must add to the usual conduction processes to model solar cells, trap assisted tunneling and Poole-Frenkel effect especially in solar cells where a higher concentration of defects is expected. The only way to separate the different mechanisms is a study versus temperature because they are all represented by an exponential and for low voltages, probably both recombination and trap assisted tunneling intervene. The shunt resistance varies exponentially with temperature whereas series resistance increase linearly versus temperature. Such behaviors have been also observed by Veissid et al [9]. The variation of the series resistance versus temperature, could be explained by the variation of the resistivities of the different layers of the component. The series resistance is the summation of : the grid resistance, contact resistances, sheet resistance, base resistance and back contact. The resistivity of the base varies exponentially in our temperature range with a minimum at about 100K [1]. The emitter is degenerated and we suppose that the variation of its resistivity shows the same quasi linear dependence versus temperature than the metal of the contacts [10]. The ohmic contact is always in fact a very bad Schottky junction with very high tunnel effect probability. So, if it varies versus temperature, its resistance lowers when temperature increases. Consequently we can suppose that the series resistance of our cells is dominated by the front grid and by the diffused layer.

The comparison of solar cells made with different materials has shown, as it could be expected, that the recombination current is essentially due to the quality of the material. However, it is probable that the recombination current also contains a part of surface recombination The origin of the tunneling current is the presence of higher defect densities but they can be introduced during the processing of the device.

## CONCLUSION

We have shown that for solar cells we must add to the usual two exponential model (diffusion and recombination) trap assisted tunneling current and field assisted recombination. The recombination current is essentially due to recombination in the SCR and depends on the quality of the material. The tunneling current is also due to the presence of higher defect densities in the material but these defects can be introduced during the process. This study was originated by the intention of finding the parameters that influence the fill factor of our cells. An easy and rapid simulation using the double exponential model shows that series resistance and recombination current at high voltages are determinant on the value of the fill factor whereas shunt resistance and the exponential at low voltages are less important.


ACKNOWLEDGEMENTS

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