

Influence of concentration of dopants in the behavior of photovoltaic cells

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ABSTRACT

The working characteristics of a solar cell are affected by various parameters of construction and operation. The construction parameters are responsible for the quality of operation of the solar cell. Computer modeling of photovoltaic cells has proved to be an important tool for the understanding and development of this technology. One of the main features to be addressed in this context is the operation of the junction of N and P type semiconductors of a solar cell and how it is affected by the change of the physical characteristics of the materials that compose it, especially the change in the concentration of dopants.

KEYWORDS: photovoltaic cells, dopants, physics of semiconductors, valence layer

1. INTRODUCTION

The world energy production in the last two centuries has been based mainly on the exploitation of fossil fuels like oil, coal, gas, among others, making the economy of many countries become dependent on an energy matrix that is highly damaging to the planet. But the share of renewable energy sources, especially solar energy, has gained prominence in the world. This can be seen in Germany, with the installation

in 2010 of 6,500 MW, totaling 16,300 MW of solar PV in the country [1].

This situation is not exclusive to developed and rich countries; this may be the future trend in underprivileged areas of difficult access. As is the case of the Amazon forest in Brazil, where it operates the largest isolated diesel system in the world and the advance of solar photovoltaic energy allows isolated communities access to electricity and all its benefits [2].

The search for improvement in the solar photovoltaic conversion process is gaining importance due to the large number of applications that are possible with this technology. The applications range from portable charges for electronic devices like a few watts cell phones to up to hundreds of megawatts power plants supplying power to thousands of families.

In the middle of this process, the perfect balance between the types and concentrations of dopants and how they interfere with the photovoltaic conversion process deserves special attention [3]. Each of these dopants, either to the N type semiconductor (Arsenic - As; Antimony - Sb; Phosphorus - P) or P type (Boron - B; Aluminum - Al; gallium - Ga; Indium - In) alters the physical properties of the cell photovoltaic characteristics in a particular way. This is due to the fact that several factors are changed, such as the proper concentration of intrinsic silicon (Si), mainly by modifying the operating homo junction characteristics.

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The type of dopant used will influence the GAP energy of the semiconductor, affecting the shape of the minority carrier recombination. In the case of silicon (Si) the GAP energy value is 1.12 eV (electron volt). Each dopant decreases the value of the silicon GAP in a particular way. Table 1 shows the amount of energy introduced by each dopant.

The influence on the photocurrent generation process is modified according to the profile assumed by the solar cell when different types of dopants are used in the manufacturing process. This change of doping is evidenced by observing the electrical characteristics represented by solar cell I-V and W-V curves, especially in regard to short-circuit current (A), the open circuit voltage (V), the point of maximum power (W) and the efficiency represented by the fill factor [4].

Another aspect of the solar cell that is greatly affected is the PN junction. This PN junction is the region of greatest importance to a photovoltaic cell, because this site is responsible for the effective generation and conduction of electrical current for the absorption of light [5]. Usually the cells are based on homo junction cells with just one N type semiconductor and other P-type, and are used to absorb a specific range of the solar spectrum [6]. This technology is used in the cells of mono-crystalline silicon (mc-Si) with average conversion range from 14% to 17% and is currently the paradigm of manufacturing solar cells commonly used in commercial scale.

The redistribution of charge carriers in the PN junction occurs around the Fermi level of the semiconductor. This process extends over a certain length towards the side of the N-type semiconductor and P-type semiconductor. Thus in the vicinity of a PN junction a dipole is formed, consisting of donor of positive ions on the N side and acceptor of negative ions on the P side. The generated dipole creates an electric field that drives the conduction layer electron to the N type semiconductor and the gap in the valence layer to the P type semiconductor.

The dipole extends on both sides of the junction, forming a region called the depletion layer; this PN junction forms a capacitor, consisting of driving regions and regions where the depletion

Table 1. Energy value in eV for each type of dopant.

Element	Energy (eV)
(As)	0.054
(Sb)	0.039
(P)	0.045
(B)	0.045
(Al)	0.067
(Ga)	0.072
(In)	0.16

layer acts as an insulator [7]. The modification of the type of dopant used and the layer concentrations modifies the behavior of the PN junction with respect to how this dipole is generated. This is mainly due to change in length of the depletion layer in both semiconductors N and P.

The understanding on how the homo junction works from the physical construction of a solar cell and its utilization parameters is justified by the fact that the PN junction influences the electrical characteristics of the solar cell. Through computer simulation, using software such as PC1D [8], the AFORS-HET [9], PMCC [6], where the behavior of the solar cell is investigated having as a base a descriptive mathematical model, it is possible to understand its operation and how the different types of dopants and concentrations affect its operation.

2. Mathematical formulation

To calculate the behavior of the photovoltaic cell it is essential to have a mathematical model that accurately represents their electrical characteristics. This representation can be given through the electrical equivalent circuit [10], through the profile of the behavior of carriers in the P and N type semiconductors [11] or through the types of dopants used in the physical constitution of the solar cell [12]. In the homo-junction an electrical potential exists that prevents the free passage of electrons to the N type semiconductor and holes to the P type semiconductor. This electric potential is called the potential barrier. Equation (1) can estimate the value of the potential barrier [13].

$$v_{bi} = \left(\frac{k.T}{q} \right) \cdot \ln \left(\frac{N_a \cdot N_d}{n_i^2} \right) \quad (1)$$

Where v_{bi} is given in volts (V), k is the Boltzmann constant, T is the temperature in kelvin, q is the electron charge (eV). As much N_a (concentration of acceptor impurities), N_d (concentration of donor impurities) and n_i^2 (intrinsic concentration of the material) are measured in $atoms.cm^{-3}$. The value of the potential barrier is dependent on the temperature of the system. The lower the temperature of the cell, the better their performance; the fact is that electrons and holes recombination decreases due to thermal agitation. Equation 1 shows the binding of the behavior of homo-junction and the physical properties of the solar cell construction and the usage parameters.

The modification of the type of dopants, not only alter its concentration in each semiconductor (types P or N), but also influences the Si concentration. If both semiconductor types N and P are not excessively doped, the depletion region will extend significantly in both semiconductors. So, the application of a small reverse current will result in the migration of these carriers to the junction [14]. The reverse saturation current (A) affects the solar cell efficiency by decreasing the amount of carriers available for the effective generation of electricity.

When a voltage V is applied directly on the homo-junction, there is an increase of its capacitance. When the voltage V is applied in reverse the capacitance decreases. Just as there is a capacitance, there is an electric field ξ in the PN junction. Equations 2 and 3 estimate the length of the depletion layer respectively in the N and P materials based on the concentration of impurities and the inner potential [15].

$$W_n = \left[\frac{2 \cdot \varepsilon \cdot N_a}{q \cdot N_a \cdot (N_a + N_d)} \right]^{\frac{1}{2}} \cdot (v_{bi} - v)^{\frac{1}{2}} \quad (2)$$

$$W_p = \left[\frac{2 \cdot \varepsilon \cdot N_d}{q \cdot N_d \cdot (N_a + N_d)} \right]^{\frac{1}{2}} \cdot (v_{bi} - v)^{\frac{1}{2}} \quad (3)$$

Where W_n and W_p are measured in nm . The length of the depletion layer is dependent of the potential barrier v_{bi} , concentration of impurities and the material permittivity ε . The parameter v is in volts and relative to the load applied to the solar cell, this value being equal to zero if the solar cell is without load. Soon it is possible to see that the behavior of the solar cell will have its performance changed from the load to which is submitted. Equation 4 presents the mathematical modeling of the reverse saturation current [6].

$$I_0 = q \cdot A \cdot n_i^2 \cdot \left(\frac{1}{N_a} \cdot \sqrt{\frac{D_n}{\tau_n}} \cdot \coth \left(\frac{W_p}{L_n} \right) + \frac{1}{N_d} \cdot \sqrt{\frac{D_p}{\tau_p}} \cdot \coth \left(\frac{W_n}{L_p} \right) \right) \quad (4)$$

Where I_0 is measured in ampere and the reverse saturation current is directly proportional to the area of the photovoltaic cell (A) in m^2 , and to the diffusion coefficient of electrons and holes D_n and D_p which is dependent on the material. This coefficient varies with the lifetime of minority

carriers and τ_n and τ_p measured in seconds. The larger this time the greater the distance these carriers can travel in the material increasing the chances of reaching the depletion layer. Equations 5 and 6 show the photocurrent produced in the P and N type semiconductors respectively [6].

$$I_{tn} = \frac{q \cdot A \cdot F_{ph} \cdot \alpha \cdot L_n}{\alpha^2 \cdot L_n^2 - 1} \cdot \left[\frac{S_n \cdot \cosh \left(\frac{W_p}{L_n} \right) + \frac{D_n}{L_n} \cdot \sinh \left(\frac{W_p}{L_n} \right) + (\alpha \cdot D_n - S_n) \cdot e^{-\alpha \cdot W_p}}{S_n \cdot \sinh \left(\frac{W_p}{L_n} \right) + \frac{D_n}{L_n} \cdot \cosh \left(\frac{W_p}{L_n} \right)} \right] - \alpha \cdot L_n \quad (5)$$

$$I_{t_p} = \frac{q \cdot A \cdot F_{ph} \cdot \alpha \cdot L_p}{\alpha^2 \cdot L_p^2 - 1} \cdot \left[\frac{S_n \cdot \cosh\left(\frac{W_n}{L_p}\right) + \frac{D_p}{L_p} \cdot \sinh\left(\frac{W_n}{L_p}\right) + (\alpha \cdot D_p - S_p) \cdot e^{-\alpha \cdot W_n}}{S_p \cdot \sinh\left(\frac{W_n}{L_p}\right) + \frac{D_p}{L_p} \cdot \cosh\left(\frac{W_n}{L_p}\right)} \right] - \alpha \cdot L_p \quad (6)$$

Where I_{t_n} and I_{t_p} represents the photocurrent generated in the semiconductor on both the N and P sides respectively in Ampere. These currents are a function of the number of photons arriving at that particular semiconductor expressed by F_{ph} , the absorption constant α , the holes and electrons diffusion length L_n and L_p in meters, and the electrons and holes surface recombination speed S_n and S_p in m/s. The higher the surface recombination speed lower is the performance of the cell. One of the factors that influence the rate of recombination is related to surface temperature, the higher the temperature, the greater the thermal agitation and the surface recombination rate.

The reflectance is responsible for decreasing the amount of incidence of photons in the cell, reducing its ability to generate power. The absorption constant α is dependent on the material and changes according to each type of dopant used in solar cells. Equation 7 shows how the total photocurrent can be estimated, which is given by the sum of Equations 5 and 6 [6].

$$I_t = I_{t_n} + I_{t_p} \quad (7)$$

Equation 8 shows the dependence of the open circuit voltage according to the generated photocurrent and reverse saturation current. Thus one can observe that the types of dopants and their concentrations will influence the behavior of the solar cell. The terms of Equation 8 give the voltage and current, and power and current characteristic curves of the solar cell.

$$v_{oc} = \left(\frac{k \cdot T}{q} \right) \cdot \ln \left(\frac{I_t}{I_0} \right) \quad (8)$$

3. Influence of the types of dopants

In a solar cell where the base element for the formation of N-type and P-type semiconductors is the Silicon (Si), the homo-junction characteristics are affected mainly by the type of dopant used in the formation of the semiconductors, in their

concentration and in the solar cell operating temperature. The usage parameters of the solar cell are presented in Table 2.

The change in the type of dopant will directly change the value of the potential barrier and the length of the depletion layer for both the N and P sides. The main impact in this change will be visible on the reverse saturation current and the value of open circuit voltage v_{oc} . The photocurrent is almost the same for the settings of dopants being of 2.701 ampere. Figure 1 shows the variation of reverse saturation current as a function of the doping used. It may be noted that although the concentration of doping is the same, there is a wide variation in reverse saturation current, especially when the element Indium (In) is used as dopant for the P-type semiconductor.

The lower values of reverse saturation current for the Silicon (Si) cell are found for the dopants Antimony (Sb) and Boron (B); Phosphorus (P) and Boron (B) with respectively 6.06×10^{-11} (A) and 7.65×10^{-11} (A). Figure 2 shows the variation of open circuit voltage according to the variation of doping used.

It may be noted that although the variation is small in volts, the maximum in the order of 0.160 volts, when comparing the maximum values of v_{oc} of 0.630 volts for Sb and B, and 0.624 volts for P and B, and the lowest value of 0.470 volts for Sb and In, this variation will have a major

Table 2. The typical parameters of a solar cell.

Range of the spectrum (nm)	400 - 700
Radiation ($W \cdot m^{-2}$)	1000
Temperature (K)	298.15
Thickness of the N-type semiconductor (nm)	0.2
Thickness of the P-type semiconductor (nm)	300
Solar cell area (cm^2)	100

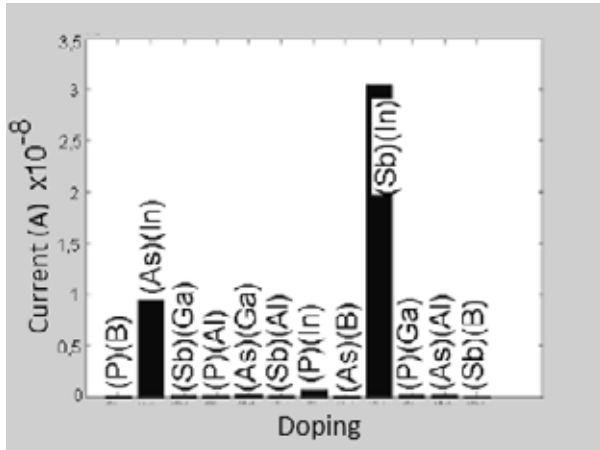


Figure 1. The value of reverse saturation current based on the type of dopant.

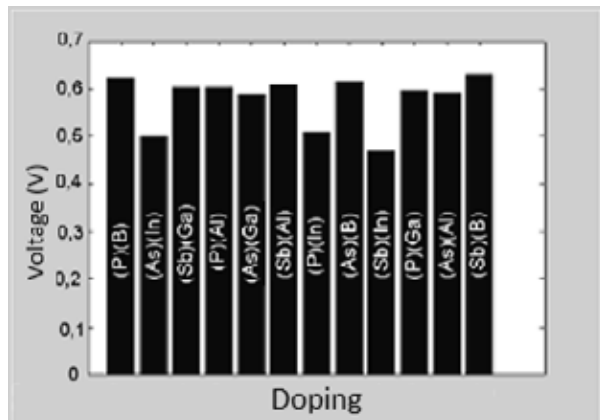


Figure 2. Graph of v_{oc} as a function of the type of dopant.

impact on the characteristics of voltage and current of the cell, as it will move the point of maximum cell efficiency, it represents approximately 25.39% of variation in the value of v_{oc} due to modification in the types of dopants.

Figure 3 shows the variation of the maximum generated power by the solar cell as a function of the doping. By comparison of Figures 2 and 3 it can be seen that the variation of maximum power generated by the solar cell is directly proportional to the voltage v_{oc} produced in each setting, with a maximum power of 1.419 (W) for Sb and B, the maximum power of 1.404 (W) for P and B and maximum power of 1.010 (W) for Sb and In.

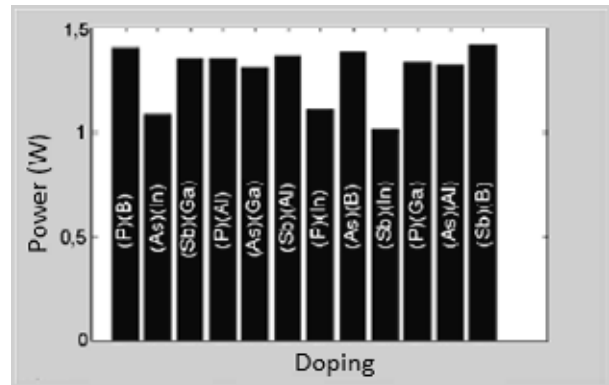


Figure 3. Graph of maximum power based on the type of dopant.

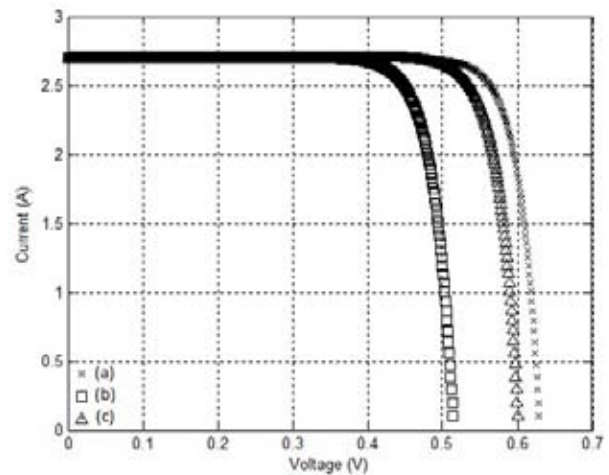


Figure 4. Graph I-V of the solar cell doped with Sb and B (a), Sb and In (b) and P and Al (c).

Figures 4 and 5 show the graphs with the electrical characteristic for the cell doped with Sb and B (a) and Sb and In (b), P and Al (c). The maximum solar cell power doped with P and Al is 1.346 (W). The difference between the highest cell power doped with Sb and P and the cell with Sb and In is 28.83%. However the difference between the cell power doped with Sb and B and the cell doped with P and Al was 5%. The difference in power between cells of Sb and B to the cell of P and B is 1.06%.

It may be noted that depending on the type of doping, a large difference can be found in the solar cell performance. This difference can be significantly observed that the conversion

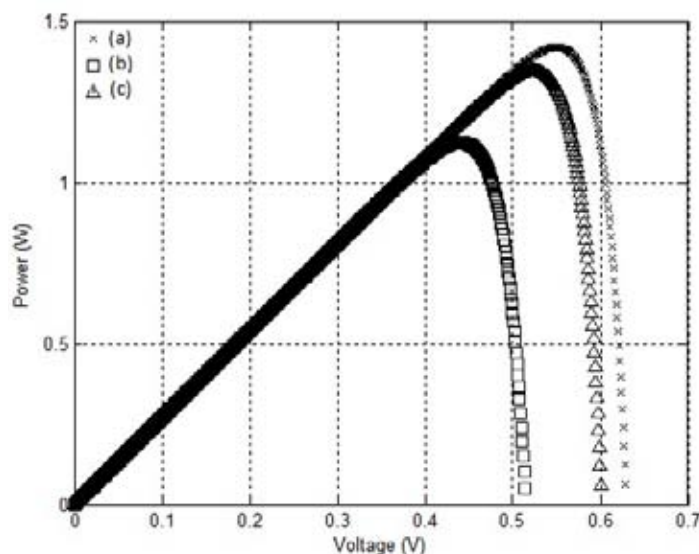


Figure 5. Graph W-V of the solar cell doped Sb and B (a), Sb and In (b) and P and Al (c).

efficiency of solar cell is in the range of 17% to 23%.

CONCLUSIONS

Through the study of the homo-junction behavior depending on the types of doping used, it is possible to observe that the doping is of appreciable influence in the behavior the photovoltaic cell. In this case, both the behavior of the potential barrier as the length of the depletion layer for both the N and P sides impacted directly on the chosen configuration. This will result in direct influence on the characteristic of voltage and current of the solar cell. The difference between the value of potential barrier in the cells doped with P and B in relation to the cells doped with Sb and B is about 0.99%. This is because the types of dopants influence the size of the depletion layer in both the N and P sides, causing a difference of 1.32% and 0.32% lower respectively. Although Boron (B) being the dopant at P side in both configurations of the cells, the differences shown in their characteristics are due to the change in the intrinsic concentration of Silicon when it is added to a particular type of dopant.

The research on the physical characteristics of photovoltaic cells by means of computer simulation based on mathematical models is of fundamental importance for the correct understanding of their

behavior. Without a doubt, one of the main aspects to be modeled and studied is the behavior of the depletion layer. If this layer for some reason presents the cell saturation by excessive concentration of dopants, it can have a momentary interruption in the operation, or there may be changes in operating characteristics in the case of substitution of dopants.

The doping can affect the performance of the cell up to 6%. This may seem minor, but is an extremely high value since a single layer photovoltaic cell presents efficiency ranging from 17% to 23%, assuming that the value of the maximum power point operation can vary by about 30%.

Thus, knowing the operation and characteristics, how they are influenced and what are the factors affected by the behavior of the depletion layer is of paramount importance for its perfect understanding, and allow exploring new paths for improving the efficiency of photovoltaic cells.

REFERENCES

1. Solar photovoltaic's, 2010, A record year in all respects, European Photovoltaic Industry Association, Press Release, 03/03/2011.
2. Matos, F. B., Camacho, J. R., Rodrigues, P., and Guimarães Jr. S. C. A Research on the use of energy resources in the Amazon.

- Renewable and Sustainable Energy Reviews, n. 15, pp. 3196 - 3206, 2011, doi:10.1016/j.rser.2011.04.012.
3. Matos, F. B. and Camacho, J. R. 2008, Simulação da Influência dos Diferentes tipos de Dopantes no Comportamento da Homojunção de Célula Fotovoltaicas Baseadas em Silício. *Eletrônica de Potência*. Volume 13, no. 4, p. 225-230.
4. Matos, F. B. and Camacho, J. R. 2007, A model for semiconductor photovoltaic (PV) solar cells: the physics of the energy conversion, from the solar spectrum to dc electric Power, ICCEP '07. International Conference on Clean Electrical Power, doi: 10.1109/ICCEP.2007.384236
5. Brum, J. A. 1983, Ligação química em semicondutores, Dissertação de Mestrado, Universidade Estadual de Campinas. Instituto de Física.
6. Matos, F. B. 2006, Modelamento Computacional de Células Fotovoltaicas Baseadas nas Propriedades Físicas dos Materiais. Universidade Federal de Uberlândia, Dissertação de Mestrado.
7. Hummel, R. E. *Electronic Properties of Materials*. 3^a Ed. Springer Verlag, Londres, UK 2001.
8. Belghachi, A. and Helmaoui, A. 2008, Effect of the front surface field on GaAs solar cell photocurrent, *Solar Energy Materials and Solar Cells*. n. 92, p. 667-672.
9. Zhao, L., Zhou, C. L., Li, H. L., Diao, H. W., and Wang, W. J. 2008, Design optimization of bifacial HIT solar cells on p-type silicon substrates by simulation, *Solar Energy Materials and Solar Cells - Elsevier*. n. 92, p. 673-681.
10. AlRashidi, M. R., AlHajri, M. F., El-Naggar, K. M., and Al-Othman, A. K. 2011, A New Estimation Approach for Determining the I-V Characteristics of Solar Cells, *Solar Energy*, n. 85, p. 1543-1550.
11. Bothe, K., Krain, R., Brendel, R., Falster, R., and Sinton, R. 2010, Determining the Bulk Lifetime of Unpassivated Multicrystalline Silicon Wafers, 25th European Photovoltaic Solar Energy Conference, Valencia, Spain, 6-10 September.
12. Matos, F. B., Camacho, J. R., Guimarães, S. C., and Salerno, C. H. 2006, Photovoltaic (PV) Cell Voltage-Current Characteristic based on Physical Properties, VII International Conference on Industry Applications - Induscon.
13. Martino, J. A., Pavanello, M. A., and Verdonck, P. B. 2003, *Electrical Characterization of MOS Technology and Devices*, Editor Thomson, São Paulo (In Portuguese).
14. Nelson, J. 2003, *The Physics of Solar Cells*, Imperial College, Londres, UK.
15. Messenger, R. and Ventre, J. 2000, *Photovoltaic Systems Engineering*, CRC Press.