SPEARMAN´S MATRIX FOR PRELIMINARY ANALYSIS OF SOLAR-CELL DATA

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I. Introduction

With the advances of computational hardware in the last decade and the development of libraries in several computational languages, the analysis of large quantites of data became much easier. Here, we focus on the use of Spearman's Matrix as an option for preliminary data analysis of solar cells developed in our lab. The correlation matrix allows to verify the compatibility between the experimental data and their expected behavior. Indications of aspects to be improved in the sample´s architecture or in the fabrication process are immediately highlighted by the correlation values.

II. Spearman's correlation coefficient

Spearman´s rank correlation coefficient, or Spearman ρ, is a nonparametric measure of rank correlation [1]. The coefficient assesses how strong the relationship between two variables can be described using a monotonous function [2]. The advantage over Pearson´s correlation is that Spearman's correlation evaluates monotonous relationships, whether linear or not. Spearman's ρ correlation will be high, with |ρ| close to 1, when the variables can be related by any monotonous (increasing or decreasing) function.

III. GaAs solar cells at LNMS-IFUSP

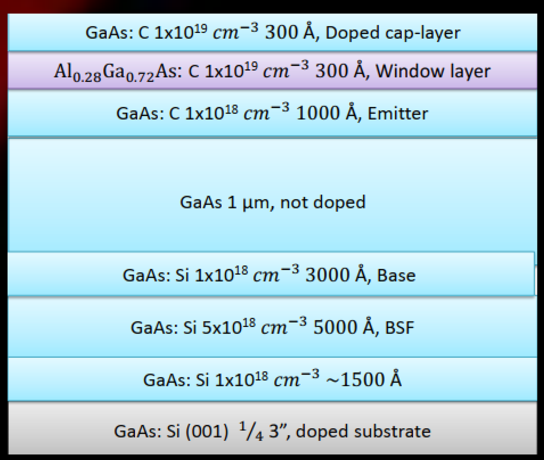

Figure 1: Typical PIN structure fabricated at LNMS-IFUSP.

Several PIN structures (Figure 1) of GaAs solar cells were designed, grown by molecular beam epitaxy (MBE), processed by photolithography in a clean room into 2×2 or 5×5 mm² devices, and finally characterized using a class AAA solar simulator and standard AM1.5G conditions. Only one layer was changed from sample to sample (figure 1).

IV. Equations for a PIN structure

Based on the equations commonly used to describe a PIN junction solar cell, one may expect correlations between some parameters that were measured. The short-circuit current J_{SC} should increase with the intensity of the radiation I_L, because

$$J_{SC} = q \int_{h\nu=E_{gap}}^{\infty} \frac{dN_{ph}}{dh\nu} d(h\nu) \sim I_L$$

From the equation that describes the illuminated solar cell

$$I = I_L - I_0\left[e^{\frac{q(V+IR_S)}{nkT}} - 1\right] - \frac{V + IR_S}{R_{sh}}$$

one can conclude that

$$I_{sc} = I_L - I_0\left[e^{\frac{q(I_{SC}R_S)}{nkT}} - 1\right] - \frac{I_{SC}R_S}{R_{sh}} = \left(\frac{R_{sh}}{R_{sh}+R_S}\right)\left(I_L - I_0\left[e^{\frac{q(I_{SC}R_S)}{nkT}} - 1\right]\right)$$

Thus, the short-circuit current I_{SC} should decrease with the dark current, with the series resistance R_S and with the shunt resistance R_{sh}. However, it should increase with the ideality factor n and absolute temperature T. The fill factor FF should increase with the maximum power P_{max} and decrease with the open circuit voltage V_{OC} and short-circuit current J_{SC}, because

$$FF = \frac{P_{max}}{V_{OC}\, J_{SC}}$$

V. Matrices of correlation coefficients

Spearman´s correlation matrices were constructed from our experimental data to check if the results were in accordance with the equations presented above. The correlation coefficients were ordered in the matrices, relating variables two by two, and only correlations larger in modulus than 0.3 are shown (below 0.3, data are considered uncorrelated). A matrix can include the data of many different solar cells‒as in figure 2‒or of a single device, as in figure 3 and 4, to analyze a specific behavior.

Figure 2: Spearman correlation matrix containing 2470 data from several solar cells.

Figure 3: Correlation matrix of sample #3908 where the highly doped GaAs cap layer was not removed (see figure 1).

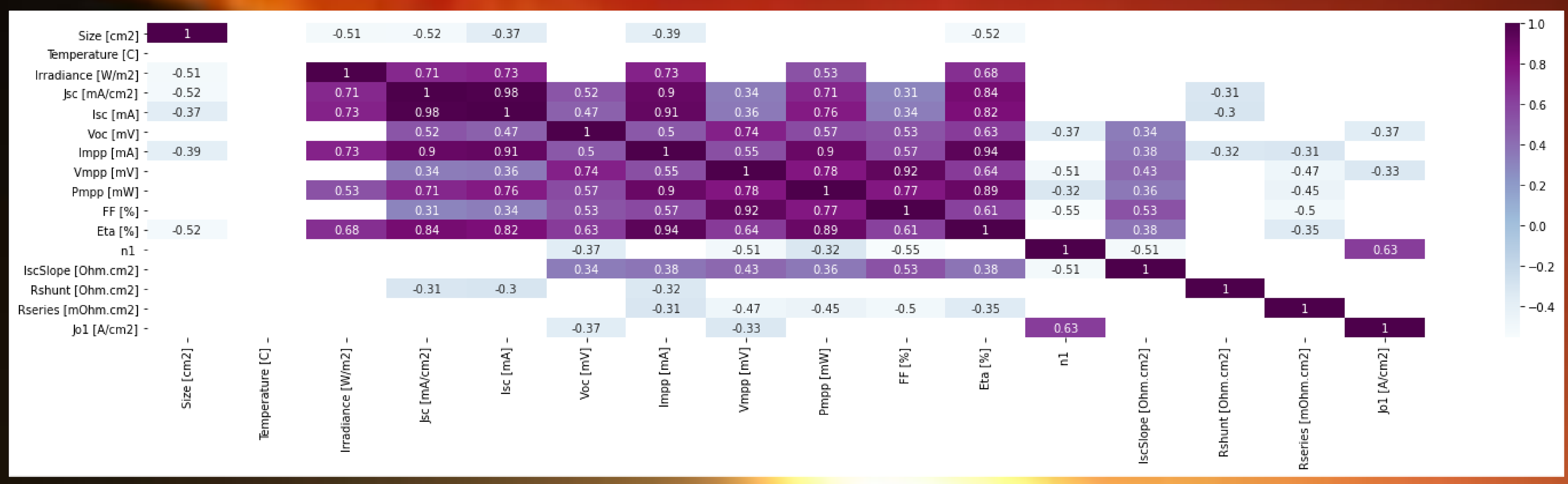

Figure 4: Correlation matrix of sample #3908 after removing the highly doped GaAs cap layer in the optical area of the device

VI. Analysis

Table 1 shows the expectation of the main correlations in our samples‒according to the equations shown earlier‒and the respective results from figures 2-4. One can see that some of the signs are inverted (red data) when compared to the predictions, meaning that the main parameter increased when it should have decreased, or vice versa. This is for instance the case for sample #3908 where it seems that there was a problem during processing or fabrication of the ohmic contacts (figure 3 and 4), whereas it usually didn´t happen with the other cells (figure 2). We can also observe that, when the highly doped GaAs cap layer (figure 3) of sample #3908 was specifically removed (figure 4) in order to reduce the absorption by free carriers, the relation between the efficiency η and the irradiance changed drastically, as expected.

Table 1: Summary of the main correlations addressed here

Main	Dependency on	Expected correlation	Correlation (Figure 2)	Correlation (Figure 3)	Correlation (Figure 4)
η[%]	R_S [mΩ.cm²]	negative	-0.75	|ρ| < 0.3	-0.35
η[%]	R_{sh} [Ω.cm²]	positive	-0.76	|ρ| < 0.3	|ρ| < 0.3
η[%]	J_{SC} [A/cm²]	positive	0.88	0.73	0.84
J_{SC}[A/cm2]	I_L [W/m²]	positive	-0.84	-0.66	0.71
FF[%]	P_{max} [mW]	positive	0.44	|ρ| < 0.3	0.77
FF[%]	V_{OC} [mV]	negative	0.58	|ρ| < 0.3	0.53
FF[%]	J_{SC} [A/cm²]	negative	0.57	-0.59	0.31
J_{sc}[A/cm2]	J_0 [A/cm2]	negative	-0.74	0.54	|ρ| < 0.3
I_{sc}[mA]	R_S [mΩ.cm²]	negative	-0.63	|ρ| < 0.3	|ρ| < 0.3
I_{sc}[mA]	R_{sh} [Ω.cm²]	negative	-0.64	-0.41	-0.3
I_{sc}[mA]	n	positive	-0.62	0.43	|ρ| < 0.3
I_{sc}[mA]	T [°C]	positive	|ρ| < 0.3	0.31	|ρ| < 0.3

VII. Conclusion

- Spearman´s correlation matrix allows to check the compatibility between the experimental data and the proposed model.
- Information about how to improve the devices is immediately highlighted, as was the case for the contact problem or doped cap-layer removal.
- However, as the correlation does not imply causality, it should only be used as a very fast and practical pre-analysis method that points out aspects that should be addressed with more care.

VIII. Acknowledgments and references

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