Modeling of TLM measures in heterojunction solar cells.

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Abstract: This work uses a simulation based on the program LTspice with data provided by a Fortran based program in order to evaluate the contact resistivity of a layer of MoOx on top of a sample of n-Si to examine their properties when used in heterojunction solar cells. This is done following a model that uses sheet resistivity and the finite element method to generate a resistor network representing those elements that imitates the TLM technique in the microscopical order. We will use the simulation in order to measure the resistance of our system for different distances between electrodes and thicknesses of the MoOx layer to evaluate the influence of that thickness in the contact resistivity and other properties.

I. INTRODUCTION

Solar cells in order to work effectively need to separate both types of charge carriers and herd them to their respective contact regions. In the first place this was accomplished with dopants that boosted conductivity in one of them while decreasing it in the other, however this hits a wall because of the Auger recombination which limits how efficient it can be.

A heterojunction solar cell is made of Si with a thin layer of another material (in our case MoOx) in order to obtain cheaper highly efficient energy conversion by introducing the needed asymmetry in carrier conductivity, blocking one type of charge while letting the other through, they also tend to have a lower temperature coefficient which makes them more efficient at high temperatures, these are not the most effective solar cells but they can be very cost effective.

MoOx is thermally evaporated over the n-Si material and favors ohmic contact formation by working as a hole-selective contact (it extracts holes and blocks electrons) and has shown a good power conversion efficiency in conjunction with n-Si. It is also easy to deposit, with its low melting point it maintains a high oxidation state and has a big chemical potential which induces a big work function that creates in the interface n-Si/MoOx an inversion layer with an accumulation of holes making it take p-type behavior.

The TLM technique in microscopical dimensions is used to measure resistivity in multilayer systems and as such, works well for our case of heterojunction silicon solar cells, calculating sheet resistance in a single layer.

The Finite element method we use for our simulation is a numerical technique that consists in the fact that to evaluate a complex model like our system would be, we divide it in a number of more simple non-intersecting domains (the finite elements) each with its own value connected by nodes.

In our case as we will explain later it will be useful to model the different layers along with the precise electrode lengths and separations.

In this work we have not simulated a solar cell since we only use a resistor network and the equivalent circuit of a solar cell would be more complex (including diodes among other things) but it serves to examine the n-Si/MoOx interface for different thicknesses of MoOx.

II. TLM MEASURING SYSTEM.

The TLM system consists on having several electrodes of the same dimensions but with different distances between them on top of a material and measuring the current for a set of tension values in order to obtain the total resistance. From that we can deduce the current transfer length, the contact resistance, contact resistivity and the sheet resistance (which will depend on the width of the electrodes that is a known value).

The contact resistance is the resistance between the semiconductor material and the contact (and in our case also between the different layers), which depends on the materials of the system and the doping of the semiconductor (lower resistance values for more heavy doping), it is equivalent to the resistance of an additional length of the semiconductor.

That additional length of the semiconductor is the current transfer length.

Contact resistivity is the contact resistance in all the contact surface (current transfer length*width of the electrodes).

The sheet resistance is the resistance per square of the semiconductor.

The total resistance will be obtained by following Ohm's law:

$$Rt = \frac{V}{I} \quad (1)$$

Once obtained the total resistance also gives:

$$Rt = 2 * \mathrm{Rc} + \frac{Rs * s}{W} \quad (2)$$

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Where Rc is the contact resistance, Rs the sheet resistance, s the distance between electrodes and W the width of the system.

The values can be obtained by making the representation of total resistance as function of the distance between electrodes and extracting the linear formula:
- The contact resistance will be half the resistance value for s=0.
- The current transfer length is half the s value for Rt=0 (in absolute value).
- The sheet resistance is the slope of the linear representation multiplied by the width of the electrodes.
- The contact resistivity is obtained following the formula:

$$\rho c = (Rs) * (Lt^2) \quad (3)$$

III. SIMULATION MODEL

The real object we are going to simulate will be according to this schematic:

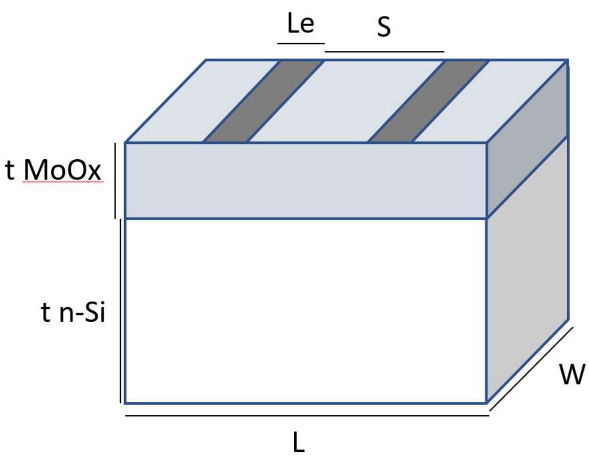

Figure 1: Schematic of the real system.

Where we have **L** the length of both layers, **Le** the length of the electrodes, **S** the separation between electrodes, **t n-Si** the thickness of the n-Si layer, **t MoOx** the thickness of the MoOx layer and **W** the width of the system (since our model is 2-D and this would be the third dimension it will be the same for all our elements).

In order to simulate TLM transmission in a heterojunction solar cell composed by a layer of MoOx on top of a sample of n-Si, we have used a model in which we use a resistor network to represent the materials determining the value of each resistor by using the formula:

$$R = \frac{\rho * (\frac{L}{n1})}{W * (t/n2)} \quad (4)$$

Where ρ is the resistivity of each material, n_1 the number of resistances along the length, n_2 the number of resistances across the thickness and t the thickness of the layer in question.

Resistances in the x direction will have different values than resistances in the y direction since their L and t will be inversed.

Each resistance in the model represents the resistance of a block of material in a direction.

The model is connected to a generator by two electrodes on the system's surface.

To make a better representation of the model the different resistances represent different distances depending on their position following the finite element analysis and namely, dividing the model in three areas: the one between the electrodes, the one below the electrodes and the rest of the system.

If we did otherwise the model would be quantized and dependent on the length of our system and the number of resistances used in the model which would cause resolution loss problems, especially where the length of electrodes and their separation is concerned.

With this system we can however input any electrodes size and separation we wish to evaluate.

In order to use a great number of resistances that would be impossible using the LTspice manually we have devised a Fortran based program that will create the file compatible with LTspice using our designated number of resistances, dimensions of the system, resistivity of the materials, length and separation of the electrodes on the surface and thickness of MoOx layer.

For this study the fixed values will be given in the following table:

Resistors in the x direction	Resistors in the y direction
50	50
L (cm)	t n-Si (cm)
0,2	0,018
W (cm)	Le (cm)
0,005	0,05
Resistivity MoOx (Ω*cm)	Resistivity of the n-Si (Ω*cm)
100000	4,2

Table 1: Values of our system.

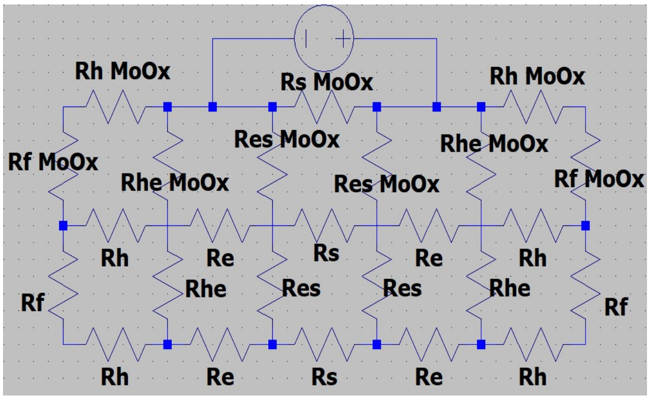

Figure 2: Simplified example of the generated system with the different values used.

The different measures done will use separation distances between electrodes (100 ;200 ;300 ;400 and 500 µm) and for a MoOx layer on the surface of thicknesses of (1 ;5 ;10 ;50 and 100 nm) (with another measurement done without MoOx layer).

The LTspice simulation itself will be a measuring of intensity for tensions that go from -15V to 15V linearly with a 0.01 V step from which we will deduce the resistance.

IV. RESULTS AND DATA

Doing the steps described previously we first observe that the I(V) curve is linear with a slope that grows when the separation between electrodes diminishes, for the case of the 1 nm MoOx layer we obtain:

Separation (cm)	Conductance (S)	Resistance (Ω)
0,01	7,420E-04	1,348E+03
0,02	5,521E-04	1,811E+03
0,03	4,403E-04	2,271E+03
0,04	3,660E-04	2,732E+03
0,05	3,116E-04	3,209E+03

Table 2: Resistances for the different measurements with a MoOx layer of 1nm.

The system shows more resistance when the MoOx thickness grows.

We represent this for all MoOx thicknesses:

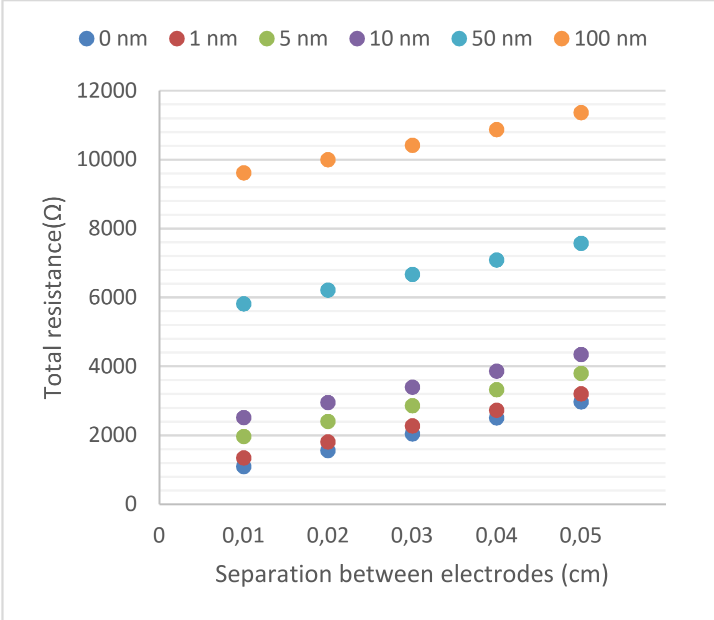

Figure 3: Resistance dependence of the electrode separation for all MoOx thicknesses measured.

We can obtain from the tendency line for each MoOx thickness (in the form y=Ax+B) the contact resistance and resistivity along with the current transfer length and the sheet resistance with the method we described previously.

We obtain the contact resistance as:

R_c=B/2. (5)

The current transfer length:

Lt=B/(2*A). (6)

The sheet resistance:

R_s=A*W. (7)

And the contact resistivity:

ρ_c=R_c*W*Lt. (8)

Following the process for all thickness MoOx values we obtain the following results:

t (nm)	Rc (Ω)	Lt (cm)	ρc (Ω*cm^2)	Rs (Ω/□)
0	3,144E+02	6,679E-03	1,050E-02	2,354E+02
1	4,405E+02	9,485E-03	2,089E-02	2,322E+02
5	7,477E+02	1,629E-02	6,090E-02	2,295E+02
10	1,020E+03	2,233E-02	1,139E-01	2,284E+02
50	2,665E+03	5,949E-02	7,926E-01	2,240E+02
100	4,566E+03	1,039E-01	2,371E+00	2,198E+02

Table 3: Contact resistance, contact resistivity, current transfer length and sheet resistance for our different MoOx thickness.

In graph form we can see:

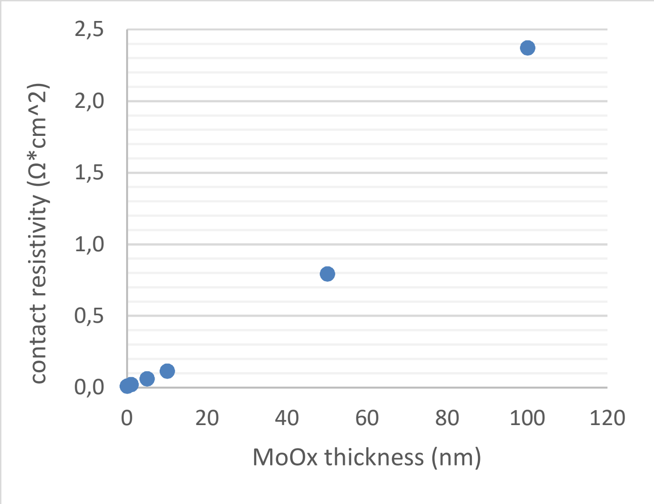

Figure 4: contact resistivity for the different values of MoOx layer thickness.

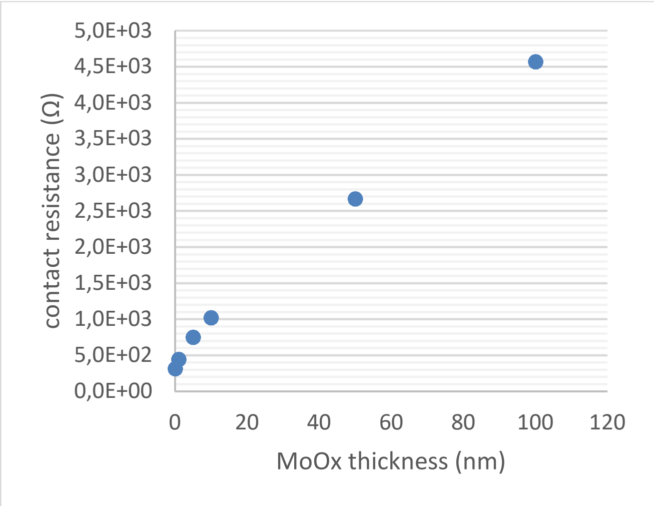

Figure 5: contact resistance for the different values of MoOx layer thickness.

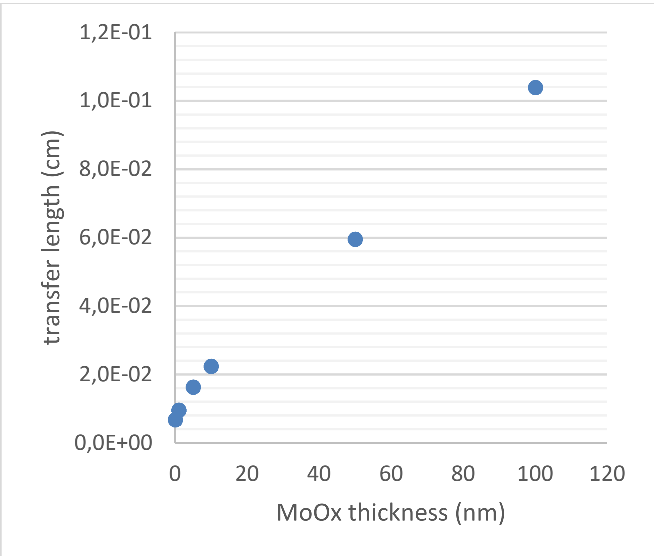

Figure 6: transfer length for the different values of MoOx layer thickness.

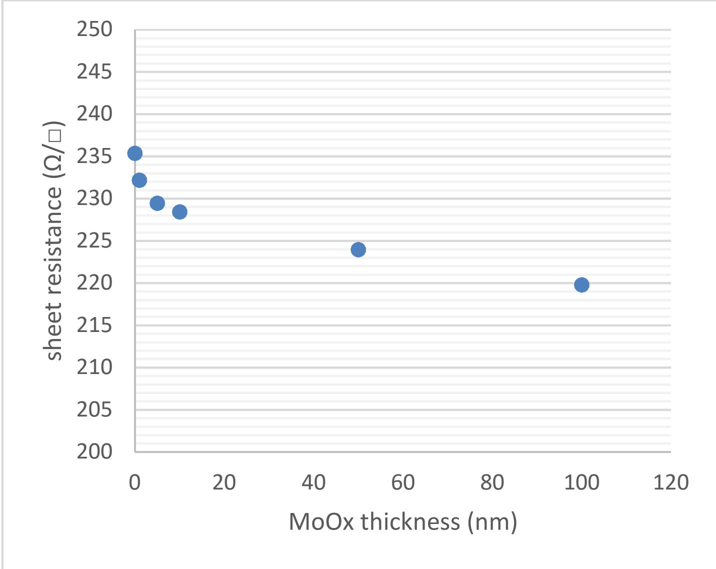

Figure 7: sheet resistance for the different values of MoOx layer thickness.

We can see that the contact resistivity increases when the MoOx thickness grows and in bigger MoOx thicknesses it grows more than if it followed the linear pattern.

Contact resistance and transfer length show very similar patterns with a linear growth when the MoOx thickness is bigger but decreases more rapidly for the MoOx thickness values of 0 and 1 nm.

The sheet resistance shows a value of 235 Ω/□ when there is no MoOx and decreases slightly to 218 Ω/□ when the thickness of the MoOx layer grows, we can see that the case where there is no layer of MoOx we find a sheet resistance (235,4 Ω/□) similar to the sheet resistance of the n-Si which we can calculate by doing $\rho_{n\text{-}Si}/t_{n\text{-}Si}$ which is 233,3 Ω/□.

Generally, we notice some change in the behavior of the bigger MoOx thicknesses compared to the thinner one which can be related to the precision of the linear regression in figure 3 from which we extracted part of our data being worse for thicker MoOx values due to the contact resistance causing a drop in voltage under the contact for the thicker values (otherwise the sheet resistance should not have noticeable changes with our values).

V. CONCLUSION

In this work we have used a simulation of the TLM pattern in order to evaluate the effect MoOx has in a heterojunction silicon solar cell and more precisely the contact resistance created between both elements.

We have worked to obtain the behavior of four elements according to the thickness of the MoOx layer in our system and we see that the contact resistance, its resistivity and the transfer length grow when the thickness of the MoOx layer increases, they are involved in energy loss and as such, high values will affect the efficiency of our solar cell. The sheet resistance of our system, however, decreases when the MoOx layer increases but it does so in a smaller factor than the others.

The MoOx layer has more noticeable effects on our system when it has a thickness superior to 10 nm (as we can see in our 50 and 100 nm cases) because of the contact resistance in the system.

This is of course not a completely accurate representation of an actual solar cell since it should be represented with a more complex equivalent circuit than a resistor network (diodes should be used) but it gives us an idea of the behavior of the materials it is made of and this method could be used for this purpose now that we have obtained these results.

ACKNOWLEDGMENTS

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