Interconnect minimisation for flexible solar cells

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Abstract

Series connections in solar cells are made to decrease the current, and therewith the transport losses in a cell. Solar energy is not converted at these interconnections and they should therefore be as small as possible. Several laser scribes and printing steps can make a series interconnection between the back and front of a cell, while insulating the conductive layers accordingly. The equipment to be designed should make interconnections with minimal size, while several criteria have to be met concerning the relative positions. The focus of this abstract is on how to come to this minimal relative positions while meeting the constraints. In our initial design, we found that the criterion that was most often broken was that the top layer was not correctly cut. The origin of this problem was the relative movement of a scribe with the substrate. Incorporating a simple feedback loop decreased the interconnection width by 16%.

1 Introduction

Roll to roll production of solar cells is a likely approach to meet high demand of solar cells in the future [1]. One of the steps in the production is to make interconnection between the solar cells. The area of this series interconnection should be minimal. Optimising the variance of all individual error contributions with, for example, dynamic error budgeting [2], is not likely to result in an optimal solution, as they will not equally influence the final width, or are not equally likely to break a criterion. Effort should be spent on those effects that influence the final results most; not on those that will not break any criterion, nor influence the final width significantly. The focus of this document is to identify which elements are responsible for the final width. Although the methodology is developed for the minimisation of series connections, it is applicable for problems where several criterions need to be simultaneously met, and the objective is to minimise some variable.

2 Methodology

Assume that we want to write two lines as close as possible, with the constraint that line 1 is always to the left of line 2. The line's position is corrupted with some disturbances, and the nominal distance between the lines is set to *b*. Refer to Figure 1. Furthermore, we set the constraint, that this actual distance between the lines, d, is smaller than some value *k*. For a given value of *b* the probability can be calculated that the lines do not cross *and* the distance is smaller than *k*: $P(d<k,\ c=1 \mid b)$, with $c=1$ meaning that the constraints are met. We can vary the maximal allowed distance *k* and find the probability for each value of *k* that the distance between the lines is smaller than it, *and* the lines do not cross. This is shown in the middle part of the figure. It shows that for increasing *k* it becomes more likely that both constraints are met. However, there is always a chance that the lines cross. This can be observed in the middle figure as the final probability goes to 0.95. In the right part of the figure, the same probabilities are calculated, but the nominal distance *b* is set to three different values.

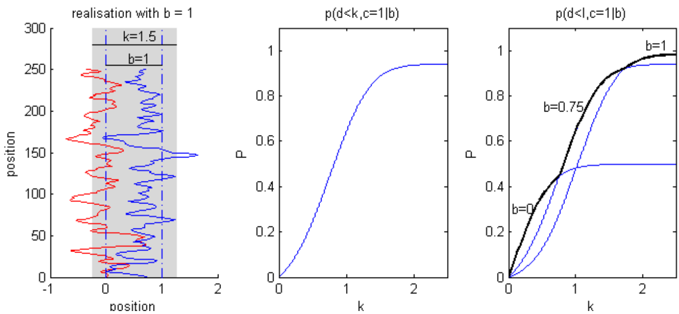

Figure 1: realisation of two lines (left), the probability that the lines do not cross and the distance is smaller than *k* for *b*=0.75 (middle), and the same probability for different values of *b* (right).

If a *maximal* distance of 1 is allowed, then the right figure shows that the largest probability to fulfil both constraints, is to set the nominal distance *b*=0.75; at *k*=1 the probability is largest for this *b*. The resulting probability to find a distance smaller than 1, without the lines crossing, is about 0.6. If the nominal distance would be chosen to be *b*=1, then the probability that the lines do not cross is larger, but the probability that a distance is smaller then 1 would be smaller. The resulting probability for meeting both constraints is smaller if we take *b*=1 than when we take *b*=0.75. The thick black line shows the highest probability to meet the constraints. This example shows the situation in which only three values for *b* are used, but of course *b* can be altered continuous. Furthermore, multiple constraints can be used. Which constraint is broken most often gives insight where to focus in the design.

3 Case

We are interested in the series connection of a solar cell. A schematic section view of an interconnect is shown in Figure 2, based on [3]. The goal of the interconnect is to connect the back contact of the right cell to the front ITO of the left cell, while insulating the conductive front from the left and right cell. Three laser scribes $p_{1,2,3}$ are made for this, and conductive and insulating inks are deposited accordingly. The criteria that need to be met for a successful interconnect are given in Table 1. In this table, *i* and *c* stand for the insulating and conductive material and the subscript left and right for the left or right edge. The width of the interconnect, the right side of p_3 to the left side of the conductive material should be minimised. This width is comparable to the distance of the previous example.

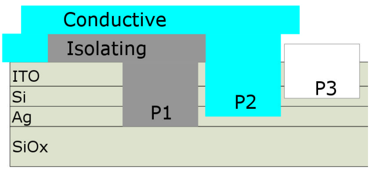

Figure 2: schematic view of an interconnect (cross section)

$p_{2,left}>p_{1,left}$	$i_{left}<p_{1,left}$	$c_{right}>p_{2,left}$
$p_{2,right}>p_{1,right}$	$(i_{right}>c_{right})$ or $(p_{3,right}>c_{right})$	$c_{left}<i_{left}$
$p_{3,right}>p_{2,right}$		

Table 1: constraints that have to be met for a successful interconnection

The processes that make the scribes and print the materials are affected by disturbances. A set of simulations is performed to determine the probability that the constraints are met, and the width is smaller than *k*. In these simulations the nominal positions and the widths of the scribes and the printed materials were altered. In Figure 3, the probability that the constraints were *not* met is plotted in blue. This probability is for the best parameter values. A width of the interconnect of less than 150 µm can be found with a probability of $(1\text{-}10^{-4})$, which corresponds to 5 errors per meter. When this width is selected, the criterion that is most often broken is $p_{3,right} > p_{2,right}$ with a probability of 44%, next is $i_{left}<p_{1,left}$ with 25% and finally $p_{2,right}>p_{1,right}$ with a probability of 16%. These broken criteria show that the scribes cannot be placed accurate enough on the moving substrate, making a short circuit. The origin of the variance of $p_{3,right}$ is broken down with dynamic error budgeting [2], as shown in figure 4. This shows that the error is dominantly determined by the support of the substrate. When the positions of the scribes $p_{1,2,3}$ are adjusted so as to track the side of the substrate, the error between these decreases significantly. Applying this in the simulation, the red line of figure 3 is found. This shows that the failrate is decreased, and that for the same number of errors, the width can be decreased from 150 μm to 125 μm. The remaining errors are now due to the uncertainty in the printing of the conductive and insulation material, which cannot be position controlled.

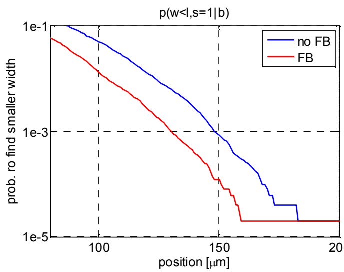

Figure 3: CFD of error with broken criteria

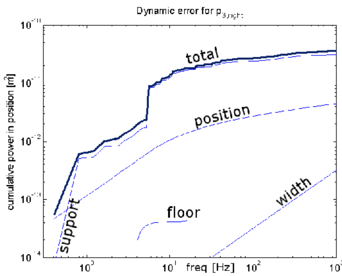

Figure 4: Dynamic error of $p_{3,right}$

4 Conclusions

A methodology is introduced that allows minimising a variable while incorporating the stochastic behaviour of the processes and the constraints that need to be met. When the constraint is found that dominantly influences the final result, dynamic error budgeting is used to see how this error can be decreased. Applying this approach to make an interconnect for a solar cell showed where our design attention should go. With a simple feedback solution the width could be decreased with 16%. The main advantage of this approached is that the *optimal* parameters are provided and which criterion is broken most often. Therewith, designers know where to focus.

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References:

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