OPTIMIZATION OF ARTISTIC CONTACT PATTERNS ON mSI SOLAR CELLS

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ABSTRACT:

The acceptance of photovoltaic modules in highly visible places like walls and roofs of buildings, or for small scale village use, is in a large part determined by nontechnical aspects, most of all by the visual appeal. The design of the surfaces of cells and modules must therefore meet two optimization criteria: High energetic output and attractive appearance. As the bus bars of the front collection grid are often considered visually annoying, we have tried to convert them into an asset by incorporating artistic shapes into them. Ten different designs have been analysed and screen printed onto 103 x 103mm^2 multicrystalline Si solar cells. For a 15 % efficient cell with standard H-pattern we have found that it would at worst be reduced to an efficiency of 14.5 % when equipped with one of our artistic bus bar designs.

Keywords: Multi-Crystalline - 1: Busbars - 2: Building Integration - 3

1 INTRODUCTION

Photovoltaic research is usually centred around conversion efficiency. However, for a wide dissemination, it seems necessary not only to have high efficiency, but to offer panels which are aesthetically pleasing and attractive to look at. This may be particularly true for building integration, small scale village use, or private use.

The goal of attractive appearance can be achieved in many ways. In the present work we have focussed on the design of the bus bars on the front side of 100x100mm^2 crystalline silicon cells, but the results are valid more generally. We have chosen the bus bars, because they are lines of sufficient thickness to be noticeable even from the distance. Currently they are mainly straight, which is, more often than not, perceived as disturbing. More interesting patterns might convert bus bars from a nuisance to an asset, which could be further enhanced by colouring them with an appropriate solder alloy.

We have created nine new patterns and modified the fine finger grid where necessary. It turns out that the loss in efficiency due to additional shading can be expected to be at most 0.5% absolute, and the loss due to additional serial resistance will be below 0.1% absolute, both for 15% efficiency with the standard bus bar pattern. All of the patterns have also been screen printed on real multicrystalline cells and subjected to first experimental tests.

2 DESIGNS

The designs are shown in Fig.1. The basic concept was to "see the module, not just the cell". The bus bars were thus designed with the intention to permit a wide variety of overall bus bar patterns of the module with just a few elementary cell patterns. For instance, patterns 1 - 4 allow to create any combination of quadratic and rectangular patterns. (Panel 1 in Fig.2.) Including the patterns 5-8 increases the range of possibilities. (Panels 2 and 3 in Fig.2.) An attempt to break out of the "two bus bars"-principle was made with patterns 9 and 10. Pattern 9 (Crack) has connection points in the middle of the four sides of the wafer, but the inner layout of the bus bar is fully asymmetric. This permits a tremendous number of ordered as well as chaotic patterns in a panel with just a single cell type! (Panel 4 in Fig.2). Clearly, electrical series connection between cells in a module cannot always be as the bus bar pattern suggests. Sometimes leads will have to be isolated and run underneath a few cells to the next connection. Pattern 10 (Hexagon) is an attempt to obtain less visible bus bars, by having a hexagonal finger web and thinner bus lines.

All designs were made with a resolution of 600 dots per inch. Finger thickness was 2 dots (85 µm). Bus bar thickness in patterns 1 - 9 was 48 dots (2.03 mm), and center-center distance of fingers was 72 dots (3.05 mm). In pattern 10 the side of a hexagon is 65 dots (2,75 mm), and the bus bar thickness is 35 dots (1,48 mm). The theoretical efficiencies as modified by additional shading, on the basis of 15% efficiency with the standard pattern, are shown in Table I.The theoretical shading caused by the patterns is shown in Table II.

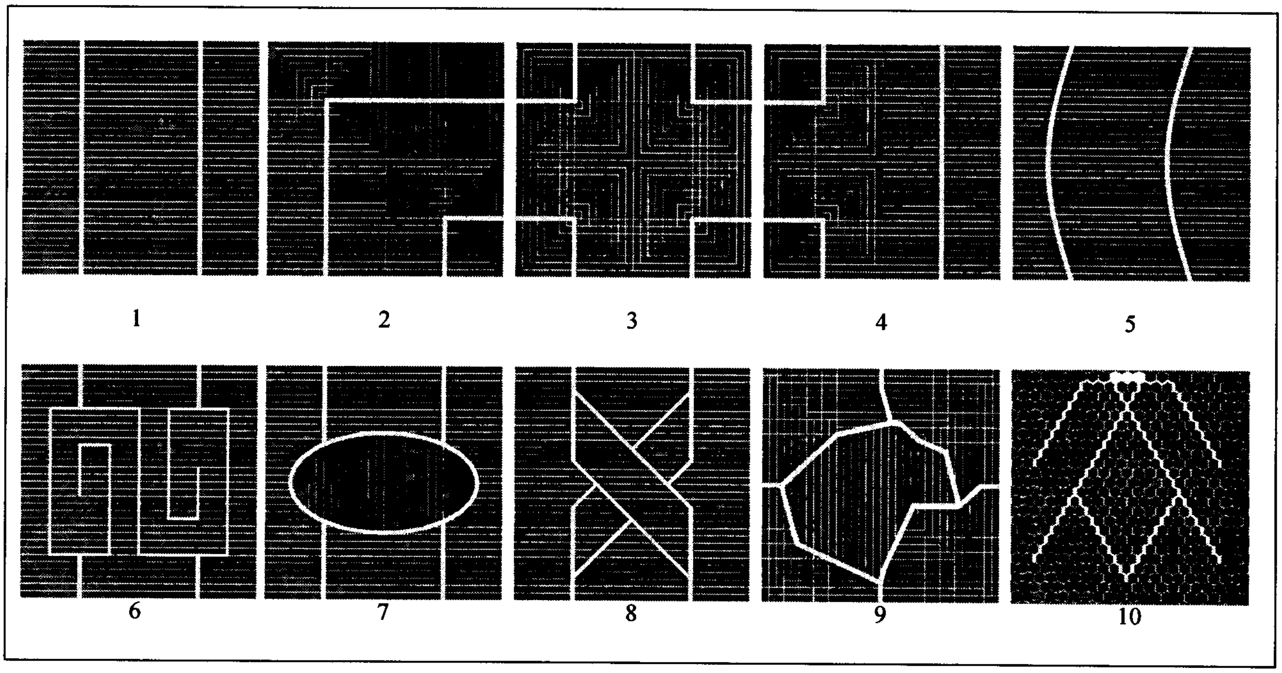


Figure 1: Front contact patterns: 1 - Standard, 2 - L, 3 - Cross, 4 - T, 5 - Sinus, 6 - Delhi, 7 - Ellipse, 8 - Braid, 9 - Crack, 10 - Hexagon

3 THEORY

Aside from losses due to additional shading, any deviation from the standard pattern 1 can be expected to give rise to additional resistive losses, which may be partly offset by reduced contact resistance losses. In patterns (5), (6), (7) and (8) we can expect negligible additional series resistance losses compared to standard pattern 1. For instance, take pattern 5 (Sinus). It is designed to give exactly the same shading as the standard pattern, by making the bus bars marginally thinner. We will neglect resistive losses in the bus bars. The resistive losses in the fingers between the bus bars will be the same as in the standard pattern. Those in the fingers on the right will be larger, and those in the fingers on the left will be smaller, than in the standard pattern. The power loss in such a finger is given by [1] as

$$P_{loss} = \rho_{lf} (j^2 d^2 b^3)/3,$$

where ρ_{lf} is the resistance per unit length of the finger, j is the generated current per unit area, d is the distance between the fingers, and b is the length of the finger to the bus bar. For $\rho_{lf} = 0.6\ \Omega/\text{cm}$ and $j = 340\ \text{A/m}^2$ we find for our parameters a total loss in the external fingers of pattern 5 of 22 mW, while the corresponding loss in standard pattern 1 is 18 mW.

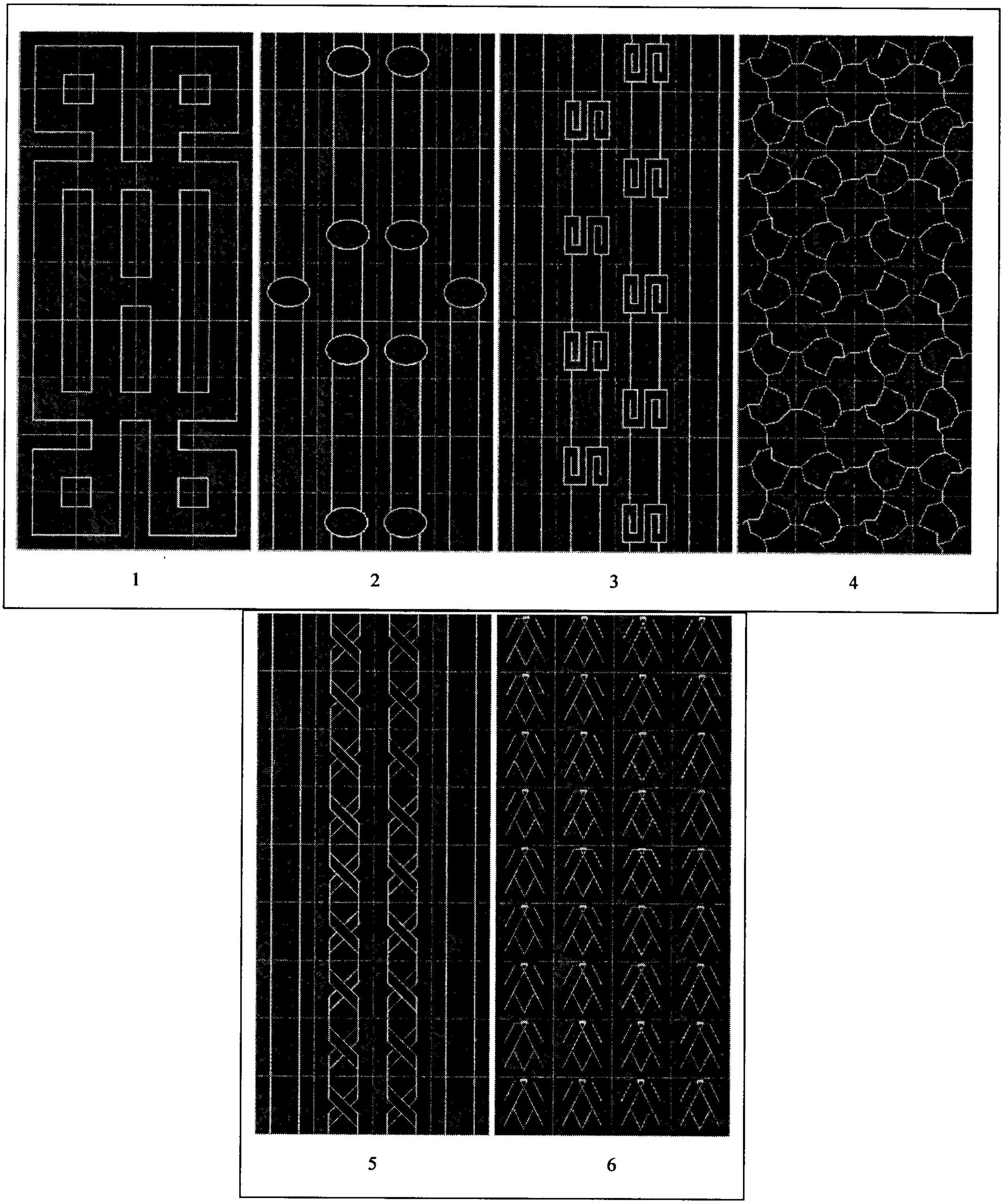
A cell of 15 % efficiency with the standard pattern would thus show an efficiency of 14.95 % with pattern Sinus.

More losses can be expected in pattern 3 (Cross), if the contact is made in the traditional way to the bus bar exits on one side. Then a major portion of the power must be transported through the fingers. An upper limit estimate is the assumption that all power is collected and transported through 16 fingers over a distance of 100 mm. There would be a loss of 90 mW, or about 6 % of the generated power. However, with interconnections of the bus bars of the cell by wires underneath the cell the resistive losses will be comparable to or less than those in the standard pattern. Similar conclusions apply to pattern 4 (T).

Pattern	Theoretical Efficiency %
1 Standard	15.00(defined)
2 L	14.95
3 Cross	14.92
4 T	14.96
5 Sinus	14.95
6 Delhi	14.70
7 Ellipse	14.72
8 Braid	14.63
9 Crack	14.65
10 Hexagon	14.52

Table I: Theoretical efficiency using different new grid patterns in comparison to the standard grid (1).

The additional series resistances in pattern 2 (L) and in pattern 9 (Crack) will lead to a decrease in efficiency below 0.1 % absolute relative to a 15 % efficient cell with standard pattern. Pattern 10 (Hexagon) could not yet by treated analytically. The sheet resistance of the emitter will play a role, because the innermost points of each finger hexagon have a farther path to the finger web than in any other pattern. On the other hand, a larger fraction of points than in the other patterns is within intermediate distances to the web. Moreover, current flow will be more homogeneous in the fingers, thereby avoiding peaked I^2R-losses.



1 2 3 4

5 6

Figure 2: The possible look of future modules

4 Experiments

Multicrystalline Eurosolare 103 x 103 mm^2 silicon wafers of 340 µm thickness and 1.5 Ωcm specific resistivity were $POCl_3$-diffused at 840 °C (30 min vapour, 60 min drive in). Exploiting the characteristics of the oven, four groups of sheet resistances were produced: 60-70, 70-80, 80-95 and 95 to 130 Ω/square. The rear side was aluminised by screen printing and diffused to obtain good contact and back surface field. The front grid patterns were screen printed with commercial silver paste using screens of 200 threads/cm. The horizontal lines of the patterns were rotated by 22 degrees relative to the threads. Since screen printing is sensitive to mechanical parameters, we tried to keep the speed of the squeegee, which was pulled by hand, to 1cm/s.

The actual shading after screen printing was determined by scanning each cell with a commercial scanner with a resolution of 600 dots per inch to obtain an image in 256 steps of grey. The screen printed lines appear relatively white, such that the pixels representing lines could be counted automatically, thereby accepting an error of mistaking bright areas of some grains as silver lines. The most probable values are shown in Column "Printed shading" in Table II. They have an uncertainty towards larger values, but certainly do not exceed the upper limits given in column 4 of Table II. The numbers suggest still non-optimal viscosity of the paste and perhaps screen thread density [2,3].

Four-point resistance measurements under reverse bias as well as non-bias conditions have also been made on many fingers on the cells. Patterns 1-9 still had many interruptions. However, pattern 10, whose finger grid is a hexagonal web, showed almost no interruptions. On this pattern, resistance from anywhere on the fingers to the nearest bus bar point always was below 250mOhm. This is explained by the many paths leading from one point to any other in this web.

Pattern	Theoretical shading %	Printed shading %	Upper limit %
Standard	6,50	9,2	10,2
L	6,79	9,4	10,5
Cross	6,99	10,0	11,3
T	6,78	9,5	10,6
Sinus	6,50	9,4	10,4
Delhi	8,40	10,7	11,7
Ellipse	8,22	10,6	11,7
Braid	8,83	11,2	12,2
Crack	8,67	11,0	12,0
Hexagon	9,51	11,8	12,8

Table II: Theoretical and practical values of the area shaded by pattern grid lines in percent compared to 100 x 100 mm^2:

5 Conclusion

We have introduced new bus bar patterns with the explicit goal of enhancing the visual appeal of crystalline silicon solar cells and modules. We showed that the fear of a large loss in efficiency is unfounded. The expected loss in efficiency is mainly due to additional shading and is less than 0.5% absolute for cells which would show 15% efficiency with the standard bus bar pattern. Resistive losses in the changed finger grid would amount to an efficiency loss well below 0.1% absolute.

ACKNOWLEDGMENT

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