SHORT COMMUNICATION

How to Design Optimal Metallization Patterns for Solar Cells

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Solar cells have a metallization pattern to collect the current. Generally, simple metallization patterns, such as the H-grid metallization pattern, a cross-hatched pattern or a full metallization, are used.

With the widely used technique of screen printing, however, virtually any metallization pattern of any topology can be realized, but the problem is how to design the optimum topology. The paper presents a design method for optimal metallization patterns. Copyright © 1999 John Wiley & Sons, Ltd.

INTRODUCTION

Metallization patterns are an essential component of many solar cells. They are generally applied on both rear and front sides of a solar cell to make electrical contacts to the cell. With, for example, screen printing almost any pattern can be printed. Optimization of patterns is generally done within a class of patterns of a certain topology. The most well known example of this technique is the optimization of the finger distance in H-grid metallization patterns.1–6

We present a design method for metallization patterns that gives an optimal metallization pattern without any pre-assumptions on the topology of the pattern. The method can be used to optimize for both maximum efficiency at a particular irradiation condition and maximum yearly yield.

PRINCIPLE OF THE DESIGN METHOD

Figures 1 and 2 illustrate the principle of the method with the help of a few fingers of an H-grid pattern.

For the sake of argument, we assume it would be possible to smear out the metallization. The smeared out metallization covers the whole cell. The more darkly coloured cross-sectional area in Figure 1 remains the same so the conductivity of the metallization remains the same. In order to maintain the right overall transparency we assign to the full metallization in this case a uniform transparency of 75% because the finger spacing is four times the finger width. In the case of Figure 2 the transparency assigned to the smeared out metallization decreases linearly from 100% at the tip of the fingers to 50% at the intersection with the busbars where the finger spacing is twice the finger width. The smeared out metallization differs from the fingers in one important aspect however: the fingers can conduct current only in the direction...
along the finger while the smeared out metallization can conduct current in any direction. This fact will be exploited to optimize the pattern further. The central idea of the new design method is the following. We split the design of the metallization pattern into two steps. In the first step we design and optimize the smeared out metallization (the right hand sides of Figures 1 and 2). In the second step the smeared out metallization is translated into a line pattern with the same total series resistance and transparency by reversing the process of smearing out the metallization. In this way we avoid the difficult problem of the direct optimization of the geometry of the metallization pattern. It turns out that we can parameterize the smeared out metallization with a relatively small number of parameters, typically 10. Therefore full optimization of the smeared out metallization is possible.

The second step is only a translation step and is necessary only after the smeared out metallization has been optimized. The series resistance due to the metallization is unchanged by the translation step because the orientation of the fingers is chosen parallel to the current flow and the cross-section of the metallization is not changed. Contact resistance and emitter losses for the line pattern resulting from the second step can be taken into account in the first step.

**MATHEMATICAL METHOD**

The smeared out metallization is characterized by its position dependent thickness $d(x,y)$. The screen printed metallization is characterized by its thickness $d_0$, its sheet resistance $\rho_{sm,0}$ and the minimum width $w$ that can be achieved. The sheet resistance $\rho_{sm}(x,y)$ and the shadow fraction $\rho_{s}(x,y)$ of the smeared out metallization to be designed can be derived directly from $d(x,y)$.

$$\rho_s(x,y) = d(x,y)/d_0 \quad \rho_{sm}(x,y) = \rho_{sm,0}/\rho_s(x,y)$$

We assume that the local current $J_{mp}$ and voltage $V_{mp}$ at maximum power point are given. Optimization for yearly yield can be achieved by using a single yearly averaged $J_{mp}$ and $V_{mp}$. The total power $P_g$ that could be produced by the solar cell without shadow and resistance losses is given by the following integral over the cell surface $S$:

$$P_g = \int_S J_{mp} V_{mp} \, dx \, dy$$
However, there are shadow- and resistive losses. On the illuminated side of the cell, the current density \( J_{mp} \) is reduced due to shadowing by the opaque metallization:

\[
J_{mp}(x, y) = J_{mp}(1 - p_s(x, y))
\]  

(3)

The ohmic loss in the metallization is determined by solving a partial differential equation for the voltage difference across the cell surface \( V(x, y) \):

\[
\nabla \left( \frac{1}{\rho_{sn}(x, y)} \nabla V(x, y) \right) = -J'_{mp}(x, y)
\]  

(4)

The current flow pattern resulting from the solution of this differential equation is the pattern that gives the least Ohmic dissipation. The differential equation must be completed with boundary conditions. The boundary conditions are a prescribed voltage at the connection to the external leads. Across other boundaries no current flow is possible. Equation (4) allows to calculate the voltage distribution \( V(x, y) \) and from that the current vector \( j(x, y) = 1/\rho_{sn}(x, y) \nabla V(x, y) \) in the metallization and the power \( P_m \) dissipated in the metallization.

The contact between emitter and metallization results in a contact resistance loss \( P_c \) and is characterized by a contact resistance \( \rho_c \). The dissipation due to contact resistance is inversely proportional to the coverage fraction \( p_s(x, y) \): the lower the coverage, the higher the dissipation.

\[
P_c = \rho_c \int_S \frac{J_{mp}(x, y)^2}{p_s(x, y)} \, dx \, dy
\]  

(5)

For the resistance loss \( P_e \) due to emitter sheet resistance, the derivation is a little more complicated. In order to calculate this loss we make the assumption that everywhere the pattern consists locally of metallization lines running in parallel. We consider the region illustrated in Figure 3. The region contains a stretch of a finger of length \( L \) and extends over a length \( s(x, y)/2 \) from the heart of the finger to the centre between two fingers. The illuminated area of this region is \( L(s(x, y) - w)/2 \). The resistance of the emitter

![Figure 3. An area of length \( L \) and width \( s/2 \) (enclosed between the two dotted lines) is used to calculate the dissipation in the emitter. The shaded areas indicate metallization fingers.](image-url)
from the centre of the finger to the edge of the finger is \( r_e(s(x, y) - w)/(2L) \). Because the current builds up linearly from 0 to halfway between two fingers to the edge of the finger, \( r_e \) must be divided by 3.

\[
P_e = \frac{1}{L} \int \frac{\rho_s s(x, y) - w}{2L} (J_{mp} L(s(x, y) - w)/2)^2 \ dx \ dy
\]

Here \( w \) is the finger width that we can achieve and \( s(x, y) \) is the distance between the fingers. We have used the relation \( s(x, y) = w/p_s(x, y) \). In this way we get for \( P_c \) and \( P_e \) expressions similar to Green.\(^8\)

The power lost due to shadowing is written as:

\[
p_s(x, y) = \int_p s(x, y) J_{mp} V_{mp} \ dx \ dy
\]

The total loss \( P_1 = P_s + P_m + P_c + P_e \) is a combination of the shadow loss and the resistive losses. \( p_s(x, y) \) can be optimized numerically by considering \( P_1 \) as a function of \( p_s(x, y) \).

**RESULTS AND DISCUSSION**

To illustrate the results of the method we consider a front side metallization for a 10 \( \times \) 10 cm\(^2\) mc-Si solar cell with screen printed metallization and two tabs optimized for yearly irradiation conditions. We compare a standard H-grid pattern with optimized finger distance and an optimal metallization with varying tab lengths. Table I shows the results for the different metallization patterns. A tab length somewhere around 7.0 cm is optimal in this case. If the tab gets much shorter, the resistance in the fingers increases; if the tab is longer, it causes increasing shadow losses without decreasing the resistance much. In practice a shorter tab may be undesired for other reasons, e.g. reduced tolerance of the cell to cracks. The example is shown here mainly to illustrate the method.

Figure 4 shows the smeared out metallization resulting from step 1 of our method in the form of a contour plot. For reasons of symmetry only one quarter of the cell is displayed. The current vectors have all been normalized to the same length to make the direction of current flow more clearly visible. Figure 5

<table>
<thead>
<tr>
<th>Pattern</th>
<th>Tab length (cm)</th>
<th>( p_s(%) )</th>
<th>( R_e(\text{m}\Omega) )</th>
<th>Loss (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H-grid</td>
<td>10</td>
<td>8.0</td>
<td>8.7</td>
<td>10.6</td>
</tr>
<tr>
<td>Optimized</td>
<td>10</td>
<td>7.8</td>
<td>9.2</td>
<td>10.5</td>
</tr>
<tr>
<td>Optimized</td>
<td>9.5</td>
<td>7.2</td>
<td>9.5</td>
<td>10.1</td>
</tr>
<tr>
<td>Optimized</td>
<td>7.0</td>
<td>6.9</td>
<td>10.4</td>
<td>10.0</td>
</tr>
<tr>
<td>Optimized</td>
<td>3.3</td>
<td>7.2</td>
<td>16.4</td>
<td>12.1</td>
</tr>
</tbody>
</table>

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Figure 4. Superposition of current vectors and contour plot of coverage fraction for a tab length of 3.3 cm
shows a metallization pattern consistent with the data from Figure 4. The metallization fingers are aligned with the current vectors. They have been tapered in order to achieve the right coverage fraction. There are some extra metallization lines running perpendicular to the current vectors. These serve to provide extra pathways in the case of interruptions. The emitter resistance loss is large where the fingers are widely spaced. In parts of the pattern where current is high (for example around the tip of the busbar), the fingers are more closely spaced. In these high current regions the fingers can be made more wide for improved printing quality without increasing the emitter sheet resistance losses. We have developed a special program for the translation step that generates an AutoCad drawing from which a film can be made directly.

We conclude that we developed a method to design optimal metallization patterns. No pre-assumption on the topology of the pattern is made. The optimal patterns differ quite strongly in shape from standard patterns in some cases, as shown in the example. The optimal patterns can be introduced in a screen printing line without extra cost, so they may be a viable alternative to standard patterns.

There are issues that still have to be addressed. One issue is how the print quality depends on the orientation of the fingers with regard to the mesh, especially for narrow fingers. Another issue is that we currently assume fixed values for the current density and voltage at maximum powerpoint. In principle these vary across the wafer due to distributed series resistance effects. Under normal operation conditions this is probably a second order effect.

An application for a patent on this design method has been filed. (Dutch patent number 1010635).

REFERENCES