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Research Article

Effect of Finger Width on the Optimal Dimensions of a Solar Cell Collection Grid

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Abstract

This article investigates the optimization of front-side metallization grids in photovoltaic (solar) cells to improve their energy conversion efficiency. Metal grids collect electrical current generated by sunlight and transfer it to external circuits. However, they introduce two major sources of power loss: shading losses, caused by metal covering part of the cell surface and blocking sunlight, and conduction losses, caused by electrical resistance within the grid and at the metal-semiconductor contact. The study compares two grid configurations: the ladder structure, consisting of two busbars connected by multiple fingers, and the comb structure, consisting of several fingers connected to a single busbar. Mathematical models are developed to calculate power losses associated with the front conductive layer, metal grid resistance, and contact resistance. We then examine the relationship between shading and conduction losses to identify an optimal balance between them. The results show that conduction losses decrease as the shading ratio increases. For example, increasing shading from 4% to 10% reduces conduction losses by approximately 90% for the ladder structure and 85% for the comb structure. This demonstrates the trade-off between minimizing shading and maintaining efficient electrical current collection. We have determine optimal grid dimensions by identifying the intersection of the shading-loss and conduction-loss curves. They find that a finger width of 250 µm provides a suitable optimum for both configurations. Beyond this width, increasing finger width has little influence on optimal finger spacing. The final optimal parameters are: Ladder structure: 250 µm finger width, 0.29 cm finger spacing, and 3% shading and conduction loss ratios; comb structure: 250 µm finger width, 0.18 cm finger spacing, and 2.63% shading and conduction loss ratios. In conclusion, both grid configurations can be optimized to reduce photovoltaic power losses. However, the comb structure offers better performance because it achieves a lower optimal shading ratio. We recommend further research incorporating rear-side metallization losses and more detailed resistance evaluations to improve solar cell efficiency.

Keywords

Solar Cell, Grid, Collection Finger, Shading Ratio, Power Loss Due to Conduction

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1. Introduction

The metallization of a solar cell is one of the essential steps in its fabrication. Since there are no semiconductor materials that are both transparent and sufficiently conductive, we are effectively forced to collect charge carriers on a metal grid that uses only a very small portion of the cell's metal surface [1-6]. The role of this grid is to collect the photogenerated charge carriers. It is designed to reduce the series resistance of the diffusion layer and to route the current as directly as possible to the contact that connects the individual cells [1, 7].

In addition, with the widespread use of solar energy in residential applications, we are seeing an increasing trend toward utilizing building facades to install photovoltaic cells, while taking into account the facades' aesthetics through the geometry of the grids. All of this has led to a proliferation of grid structures.

In an effort to optimize the geometric dimensions of the collection grid in order to minimize power losses and thereby improve conversion efficiency, several studies are being conducted. Indeed, the shading caused by the grids constitutes a form of loss, but minimizing it must not come at the expense of collecting the photogenerated carriers. In our study, we seek a compromise by plotting the shading ratio and the power loss ratio due to conduction on the same graph. From the point where the two curves intersect, and for different finger width values, we determine the optimal grid dimensions. Although Napoli et al. [8] have shown that a crisscross grid line structure always performs worse than a straight-line structure, given that cells with different geometries are generally available on the market, our study will focus on two metallization structures (ladder and comb).

2. Mathematical Theory

Figure 1 shows the scale and comb grid geometries.

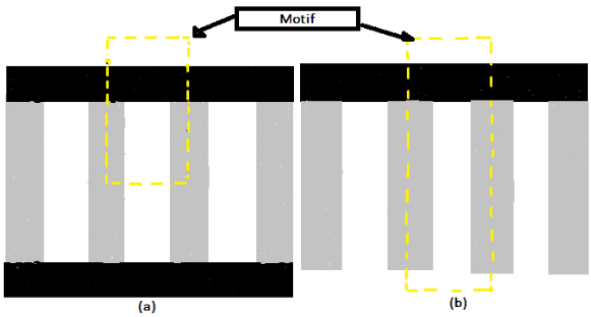

Figure 1. *Grid geometries used for the front face.*

Collector
Finger
(a): Simple linear grid (scale).
(b): Comb grid.

The ladder configuration consists of two busbars and several fingers connected to the busbars. The comb configuration, on the other hand, consists of several fingers connected to a single busbar.

After selecting the grid structures—and given that there is no mathematical method that can determine the optimal structure—we will evaluate the various power losses due to conduction.

We will consider three sources of losses due to series resistance: surface layer resistance, gate resistance, and metal-to-semiconductor contact resistance [9-13].

Shading of the grid also contributes to power loss [9].

2.1. Loss Due to the Front Layer

The current that flows through the emitter between two fingers and is collected halfway along the distance by the gate depends on the distance from the axis of symmetry, with an elementary resistance of dR.

The power loss factor of the front layer (τ_{ca}) is the ratio of the power dissipated in the resistive element dR to the power that the photovoltaic cell could supply in a half-pattern without power losses.

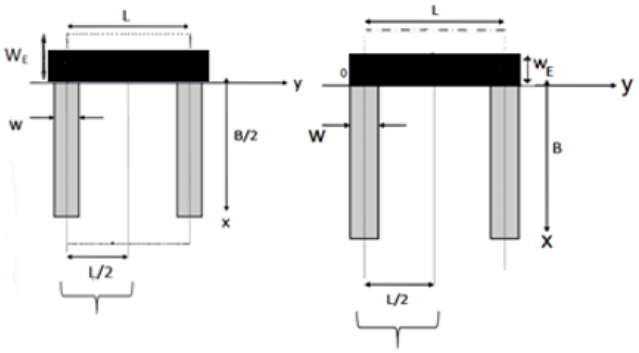

Figure 2. *Grid patterns for Echelle and Peigne, respectively.*

The power loss rate due to the front layer is given by [10, 13]:

For the ladder structure:

$$\tau_{ca} = \rho_s \frac{J_m \times L^2}{12 \times V_m}$$

For the comb structure:

$$\tau_{ca} = \rho_s \frac{J_m \times L^2 \times B}{12 \times V_m}$$

where:
L: Spacing between the fingers (cm).
ρs: Resistance per square of the front layer (Ω·sq).
Jm: Current density at maximum power (A·cm^{-2}).

Vm: Voltage at maximum power (V).

2.2. Power Loss in Gate Metallization

The power loss rate in the grid metallization (τ_m) is the sum of the power loss rates at the fingers and the busbar [10, 13].

$$\tau_m = \tau_d + \tau_c$$

For the ladder structure, it is given by the following equation:

$$\tau_m = \rho_M \frac{Jm \times L \times B^2}{12 \times W \times e \times V_m} + \rho_M \frac{Jm \times B \times L^2}{24 \times W_E \times e \times V_m}$$

For the comb structure, it is given by:

$$\tau_m = \rho_M \frac{Jm \times L \times B^2}{3 \times W \times e \times V_m} + \rho_M \frac{Jm \times B \times L^2}{24 \times W_E \times e \times V_m}$$

where:
W: Finger width (µm),
WE: Collector width (cm)
B: Finger length (cm).
d: Width of the busbar (µm).
ρM: resistivity of the metal (Ω·cm).
e: Thickness of the fingers and busbars (µm).

2.3. Power Loss Due to Metal/Semiconductor Contact Resistance

The metal collection grid provides the metal-semiconductor contact, which in turn creates a contact resistance [14, 15]. The power loss rate due to the metal-semiconductor contact (τ_{ms}) is given by the ratio of the power lost due to this metal-semiconductor contact to the power supplied by the photovoltaic cell without power loss [10, 13]:

For the ladder structure:

$$\tau_{ms} = \rho_c \frac{Jm \times L}{W \times V_m}$$

For the comb structure:

$$\tau_{ms} = \rho_c \frac{2 \times Jm \times L}{W \times V_m}$$

ρC: Specific contact resistance (Ω·cm^2)

2.4. Power Loss Rate Due to Conduction

The rate of power loss due to conduction (τ_R) is the ratio of the total power lost due to the Joule effect to the power supplied without loss [10, 13]:

$$\tau_R = \tau_{ca} + \tau_m + \tau_{ms}$$

For the ladder structure, it is given by:

$$\tau_R = \begin{cases} \rho_S \frac{Jm \times L^2}{24 \times V_m} + \rho_M \frac{Jm \times L \times B^2}{12 \times W \times e \times V_m} \\ \rho_M \frac{Jm \times B \times L^2}{24 \times W_E \times e \times V_m} + \rho_c \frac{Jm \times L}{W \times V_m} \end{cases}$$

For the comb structure, it is given by:

$$\tau_R = \begin{cases} \rho_S \frac{Jm \times L^2}{12 \times V_m} + \rho_M \frac{Jm \times L \times B^2}{3 \times W \times e \times V_m} \\ \rho_M \frac{Jm \times B \times L^2}{24 \times W_E \times e \times V_m} + \rho_c \frac{2 \times Jm \times L}{W \times V_m} \end{cases}$$

2.5. Shade Ratio

Another type of loss is characterized by a parameter called the shading ratio (τ_0), which is defined as the ratio of the metallized area to the total cell area. It is expressed by the following equation [10, 13, 16].

For the ladder-type structure:

$$\tau_0 = 2 \times \frac{W}{L}$$

For the comb structure:

$$\tau_0 = \frac{W}{L}$$

3. Results and Discussion

3.1. Effect of the Shading Ratio on the Rate of Power Loss Due to Conduction for a Ladder and a Comb

In this section, we examine the influence of the shading rate on the conductive power loss rate. Figure 3 shows the profiles of the conductive power loss rate (τ_R) as a function of the shading rate (τ_0) for ladder- and comb-type grid structures.

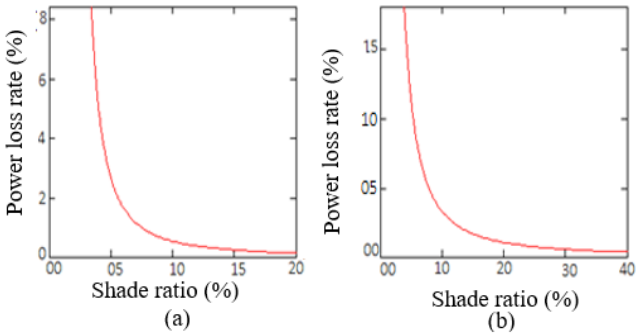

Figure 3. *Profiles of the power loss rate due to conduction as a function of the shading ratio: (a) scale and (b) comb, W = 30 µm, e = 4 µm.*

Figure 3 shows a decrease in the conduction loss rate as the

shading rate increases. The change is much more pronounced at low shading rates. For the ladder structure, we observe a -90% change in the conduction power loss rate when the shading rate increases from 4% to 10%.

As for the comb structure, we observe a reduction in the loss rate of approximately 85% for the same change in the shading ratio. When the shading caused by metallization is very high (shading ratios of more than 15% and 30% for the ladder and comb structures, respectively), the power loss rate due to conduction is low and is almost independent of the shading ratio.

3.2. Study of the Influence of Finger Width on the Optimal Point for the Ladder Structure

The rate of power loss due to conduction and the shading rate vary inversely; therefore, it is necessary to find an optimal point where both of these parameters are minimized.

The optimal dimensions are those that minimize the rates of shading and heat loss through conduction.

We optimize the spacing length L between two consecutive fingers by plotting the curves representing the functions τ0 (L) and τR (L) on the same coordinate system (see Figure 4). Next, we graphically determine, for different values of finger width, the optimal spacing length (Lop), which is the x-coordinate of the optimal point for different finger widths.

Figure 4 shows the profiles of the conduction loss rate and the shading rate as a function of L, for different finger widths.

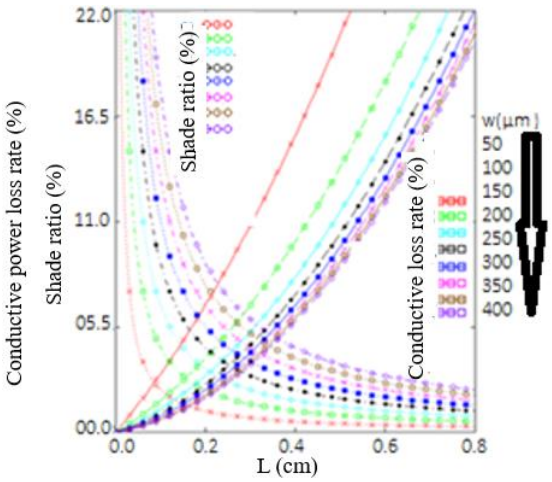

Figure 4. *Profiles of power loss rates due to conduction and shading as a function of (L) for different finger widths (W), e = 5 µm.*

We observe a slight increase in (Lop) and optimal shading and conduction loss rates as W increases. When W > 250 µm, the impact of finger width on length (Lop) remains small. In fact, finger width is an important parameter for carrier collection, but it can negatively affect cell quality due to power losses. We note here that it is not necessary to use excessively wide fingers. This is because, beyond 250 µm, the impact of finger width on the optimal length is negligible.

The results of the optimal values obtained are shown in Table 1.

Table 1. *Values of Lop, τ0op, and τRop for different finger widths (W) for the ladder structure.*

W (µm)	50	100	150	200	250	300	350	400
τ_{0op} (%) = τ_{ROP} (%)	2,60	2,70	2,80	2,90	3,00	3,10	3,20	3,30
L_{op} (cm)	0,08	0,16	0,21	0,27	0,29	0,31	0,34	0,36

3.3. Study of the Influence of Finger Width on the Optimal Point of a Comb Grid

Figure 5 shows the profiles of the shading ratio and the conduction loss ratio as a function of spacing length for different finger width values. The points of intersection indicate the optimal points. The x-coordinates represent the optimal spacing lengths, and the y-coordinates represent the optimal values of the shading ratio and the conduction power loss ratio.

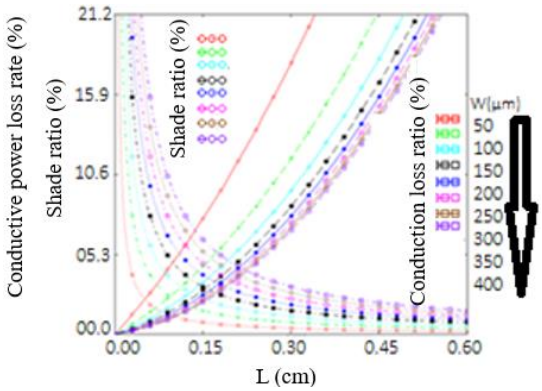

Figure 5. *Profiles of the shadowing ratio and power loss due to conduction as a function of spacing length for different values of finger width W (comb) with e = 5 µm.*

The results shown in Figure 5 are presented in Table 2.

Table 2. Values of Lop, τ0op, and τRop for different finger widths (W) for the comb structure.

W (µm)	50	100	150	200	250	300	350	400
τ_{0op} (%) = τ_{op} (%)	2,53	2,56	2,59	2,61	2,63	2,67	3,00	3,20
Lop (cm)	0,05	0,09	0,13	0,16	0,18	0,19	0,21	0,22

Figure 5 shows a slight increase in the optimal length and in the optimal rates of shading and power loss due to conduction. However, when W > 250 µm, the optimal length remains nearly constant. We will therefore choose a constant finger width of Wop = 250 µm as the optimal value.

Based on this study, when designing the collection grids on the front face of the solar cell, we were able to propose the optimal values for finger width, finger spacing, and shading ratio for ladder and comb structures. These values are listed in Table 3.

We note that the comb structure has a lower optimal shading ratio than the ladder structure.

Table 3. Optimal values of Wop, τ0op, τRop, and Lop for the two grid geometries.

Settings	Echelle	Peigne
W_{0P} (µm)	250	250
τ_{0op} (%)=τ_{Rop} (%)	3,000	2,630
L_{op} (dm)	0,029	0,018

4. Conclusion

In this article, we used mathematical models to evaluate the shading ratio caused by metallization on the front face and the conduction loss ratio on that face for two types of metallization structures (comb and ladder).

The study made it possible to determine the optimal dimensions for each type of structure. This optimization will enable us to select the appropriate grid geometry. Based on the study of the two grid models, we can conclude that:

The rate of power loss due to conduction decreases as the shading ratio increases. It is significant when the shading ratio is low, and vice versa. A study of the influence of collector finger width on the optimal parameters (optimal distance and angle between fingers, optimal shading ratio, and optimal conduction power loss) identified the optimal finger width that yields the optimal shading ratio for each of the geometries studied.

Finally, our results provide greater precision than those reported in the literature, particularly [6, 7].

Moving forward, it would be interesting to take into account the losses resulting from the metallization of the rear surface of the cell and to evaluate the resistances that cause the various losses studied.

Abbreviations

W	Finger Width (µm),
WE	Collector Width (µm),
B	Finger Length (cm).
d	Width of the Busbar (µm)
e	Thickness of the Fingers and Busbars (µm)
ρ_M	Resistivity of the Metal (?·cm)
L	Spacing Between the Fingers (cm)
ρ_s	Resistance Per Square of the Front Layer (Ω·cm)
Jm	Current Density at Maximum Power (A·cm^{-}2)
Vm	Voltage at Maximum Power (V).

Author Contributions

Moussa Camara: Conceptualization, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing

Mamoudou Toure: Conceptualization, Methodology, Supervision, Validation

Moustapha Thiame: Conceptualization, Methodology, Supervision, Validation, Writing – review & editing

Djime Conde: Conceptualization, Visualization

Minkael Yattara: Conceptualization, Visualization

Ibrahima Sory Yansane: Conceptualization, Supervision

Conflicts of Interest

The authors declare no conflicts of interest.

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