Metal Grid Finger Design Optimization for Cell to Module Ratio Using the Configurable Current Cell Technology

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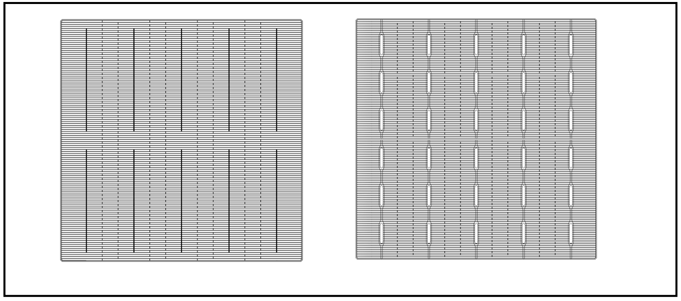
***Abstract*—The continued reduction in the amount of silver used to decrease the cost of solar energy is applied to a novel grid finger screen printed metallization design to improve the cell to module ratio for similar efficiency cells with different electrical parameters like open circuit voltage, short circuit current, and fill factor. Just as the current design of busbars has changed to incorporate segmented busbars, floating busbars or no busbars where a multi-wire module is used, the design of grid fingers needs to also evolve to eliminate redundant or unnecessary function within the solar cell device. Using a technology like the Configurable Current Cell shown in this paper will provide additional methods to reduce the amount of any metal needed to optimize the performance of a solar module by coupling the current collected by grid fingers to a particular busbar.**

***Keywords*— silver, grid finger, shading, metallization, cell to module, bus bar**

I. INTRODUCTION (*HEADING 1*)

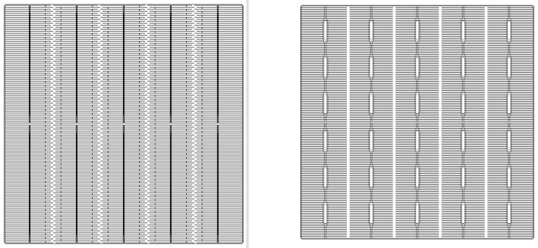
Crystalline silicon solar cells are rapidly approaching their efficiency limit in high volume production. Each part of the crystalline silicon photovoltaic device is being continually optimized for performance and cost. The International Technology Roadmap for PhotoVoltaics is an annual publication that tracks technology trends for performance and cost [1]. The ITRPV follows trends such as the transition from a "standard" emitter to a "selective" emitter, a full back surface field to a local back surface field, the number of busbars in a module as well as the cost trends for photovoltaic parts and components. This work is focused on exploring a novel application of the cell metallization steps by optimizing the cell design for improved module performance using the Configurable Current Cell, C3, technology. The C3 technology optimizes module performance by modifying the grid finger design to use less silver while taking advantage of the inherent coupling of the grid fingers to a particular busbar in the module for each solar cell. In a study by Green in 2011, the importance of changing the cell design to reduce the amount of silver used per cell was found as a necessary requirement to avoid unnecessary stress on the finite supply of silver [2]. A number of publications in the photovoltaics industry cite the need to reduce the silver consumption per cell, in fact, the International Technology Roadmap for Photovoltaics 2019 [1], reports the silver used per solar cell each year and forecasts half the amount of silver per cell by 2029. Some of the promising technologies such as fine line printing, alternative segmented busbar designs, multi-wire busbar designs have numerous publications that discuss how to optimize the performance and cost [3]. A tremendous amount of research and development has been dedicated to shrinking the printed Ag grid finger width, lowering the height of the printed grid finger/busbar, and optimizing the shading losses from the printed silver pattern while accounting for the electrical losses. Crystalline silicon solar cell devices, including mono facial, bifacial, Metal Wrap Through (MWT), and Interdigitated Back Contact (IBC) solar cells all use metal and silver is most common.

A typical solar module used in 2021 is the mono facial crystalline silicon with the "H-Bar" front silver pattern. Current industrial solar cells may have less than 5% silver shading. State of the art laboratory solar cells do not experience electrical conductivity issues when the metal to silicon interface is less than 2% [Green PERL]. Over the past 5 years there has been a shift in the design of the "H-Bar" pattern busbar to change from a simple solid rectangle that stretches the length of a solar cell to a modified design that balances solder adhesion, edge stress, the amount of silver consumed, lighted IV curve measurement pads, the silver to silicon interface, etc. The design of the busbar is being optimized for each purpose it serves within the cell design. The metal grid finger serves many purposes in the solar cell device. Grid fingers need to reduce contact resistance, transport collected carriers to the busbars, minimize optical shading, minimize electrical shading, and optimize conductivity for generated power transport in both a solar cell and solar module as part of a string.



1. Standard "H-bar" front/rear pattern for a bifacial solar cell.

Optimization of the rectangular 2-D design of the busbar into a segmented, or hollow, or stripped design has been shown to improve the Jo-metal resulting in an increase in open circuit voltage while decreasing cost and improving performance while maintaining tabbing/conducting properties. By understanding the functions played by a busbar, the pattern is improved and the solar cell benefits. When considering metal grid fingers, a great deal of development has been made on fine line printing, penetration depth, silver content, deposition layer uniformity, etc. The approach discussed in this work considers the benefits of an alternative metallization that can be used to increase the performance, decrease the amount of silver used, and add new electrical functionality to a solar cell and improves the cell to module ratio of a similar watt standard cell. Using the so called Configurable Current Cell (C3) technology the design of the solar cell is configured to improve the cell to module ratio even compared to a similar efficiency "standard" H-Bar pattern device. This is accomplished by improving the open circuit voltage by 0.5mV - 5mV per cell, by improving the short circuit current proportional to reduced optical shading coupled to the number of busbars, while maintaining the module fill factor (FF).



2. Modified "H-bar" zipper front and rear metallization pattern using so called Configurable Current Cell (C3) technology.

A systematic analysis of each process layer involving current state of the art processing will help unlock key solar cell performance enhancements that achieve specific function rather than historical application of solar cell processing. Consider the continuous development of the emitter with a selective emitter or the back surface field with a local back surface field. Metallization of solar cells needs to conduct electricity, fire through a passivation layer, make contact to the silicon surface, minimize shadowing, minimize metal laydown, etc. The goal of this work is to describe a method to further optimize the performance of a solar cell using metallization that is able to extract more power in the module compared to the conventional H-Bar pattern design.

II. DESIGN DISCUSSION

A. Design Optimization for Standard "H-Bar" Pattern

For the purpose of this optimization, a simplified discussion focused on an alternative metal "H-Bar" grid finger design for the front and rear of a bifacial solar cell is investigated, applying the C3 technology. Only metallization alternatives are described. Standard cell processing for texturing, cleaning, diffusion, and passivation are compatible. The role of the traditional "H-Bar" pattern has slightly different responsibilities depending on whether it is used on the emitter or on a surface field layer (such as an aluminum back surface field) where a high-low junction is formed. The metal on an emitter layer is understood to aid in the 2-D lateral conduction of absorbed photons while a surface field layer lowers the resistance of the bulk region and aids a more 3-D movement of collected photons.

The generated current is evenly divided across the total number of busbars. For an "H-Bar" pattern with 5 busbars and a max power point current of 10 amperes, each busbar would carry 2 amperes. Each grid finger provides a lower resistance path for a photon collected in the bulk of the solar cell and typically runs continuously laterally between each busbar, see Figure 1. Creating a region between adjacent busbars where the grid fingers are not continuous would still allow for the 10 amperes of current to be divided equally across the busbars while not significantly impacting the series resistance, $R_s$cell, and while not significantly lowering the fill factor, FF, because the distance traveled by a collected photon does not depend on direction, only the shortest path to a metal grid finger. Figure 2 shows a modified "H-Bar" pattern for the front and rear of common solar cell with a non-continuous grid finger design. The non-continuous grid finger design creates a "gap" in the region located between two busbars where no metal exist. This design increases the amount of light absorbed by decreasing the metal shaded percent of the active area on the solar cell as well as the exposed back surface region capable of absorbing light. The reduction in metal coverage also lowers the Jo-metal providing a potential boost in open circuit voltage. By limiting the metal to silicon interface a number of good things are realized if proper attention is given to maintain the fill factor.

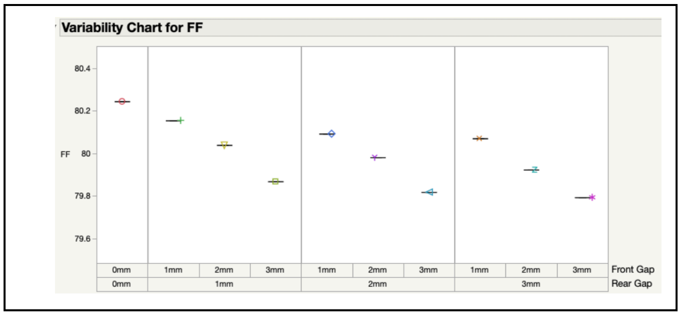
	Control	∆ Voc	∆Isc	∆FF	∆Voc, ∆Isc, ∆FF
Voc	0.680	0.683	0.68	0.68	0.682
Isc	10.300	10.3	10.35	10.3	10.35
FF	81.00%	81.00%	81.00%	80.70%	80.85%
Watts	5.673	5.698	5.701	5.652	5.707
Efficiency	23.22%	23.32%	23.33%	23.13%	23.36%

Table 1. Solar cell parameters used to determine efficiency. A 3mV higher Voc or a 0.05 amperes increases of short circuit current increases the efficiency by 0.1% absolute.

Consider the theoretical data shown in Table 1 for a modeled solar cell that has a gain in short circuit current, or a gain in open circuit voltage, or a loss in fill factor for an M2 wafer size (156.75mm each side). It is straight forward to calculate the efficiency of the solar cells by multiplying the open circuit voltage by short circuit current, by fill factor, and dividing by the surface area. Table 1 shows that by increasing the open circuit voltage by 3 mV or increasing the short circuit current by 0.05 amperes a 0.1% absolute in efficiency is achieve. Similarly, a reduction of fill factor from 81% to 80.7% will reduce the efficiency by 0.1% absolute.

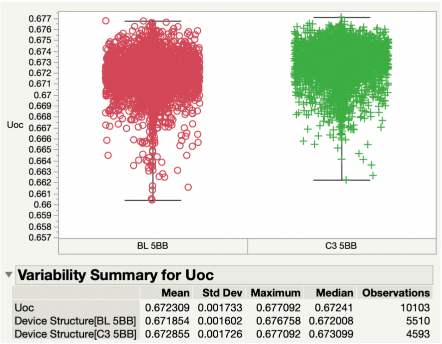
	Cell #1	Cell #2
Voc	0.6720	0.6735
Isc	10.0	10.05
FF	81.00%	80.42%
Watts	5.443	5.443
Efficiency	22.28%	22.28%

Table 2. Similar efficiency solar cells with different electrical parameters for cell #1 and cell #2.



3. Griddler model of bifacial 5 busbar mono-PERC solar cell with a varying grid finger gap on the front and rear between 0mm - 3mm.

Using the Configurable Current Cell design with the properly optimized "gap" sizes for the metal H-Bar patterns on the front and rear of the solar cell will limit or minimize the change in fill factor while gaining extra light absorption from reduced metal shading and increase the open circuit voltage by reducing the Jo-metal component for both the front and rear metallization depositions. Figure 3 shows a 5 busbar PERC solar cell structure modeled in Griddler to determine the impact of the gap size on FF performance, on both the front and rear of the solar cell. Using up to a 3mm rear side gap maintains the cell fill factor within 0.2%. Even a 2mm front gap is shown to maintain a 80.04% FF compared to the 0mm control at 80.24% Thus, by coupling the grid finger design to match to a particular busbar for current transport may result in the increase of 0.15% absolute in efficiency for the solar cell provided the gain in Voc and Isc are achieved. Figure 4 shows production line Voc data of a 5 busbar mono-PERC solar cell pilot run where all samples were processed on the same day through the same equipment where only the metallization screens were changed.



Variability Summary for Uoc

	Mean	Std Dev	Maximum	Median	Observations
Uoc	0.672309	0.001733	0.677092	0.67241	10103
Device Structure[BL 5BB]	0.671854	0.001602	0.676758	0.672008	5510
Device Structure[C3 5BB]	0.672855	0.001726	0.677092	0.673099	4593

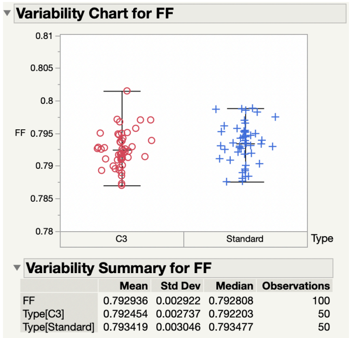
4. 5 busbar mono-PERC production line pilot data for Voc of control group and configurable current cell (C3) group for samples processed exactly the same except for the metallization screens.

III. Application and Results

Now consider two similar efficiency solar cells at 22.3% efficiency where the combination of open circuit voltage, short circuit current and fill factor are different but produce the same efficiency. Table 2 shows two such combinations. Now consider the same two solar cells as a bin of cells assembled into a 60 cell module. The series resistance for a module is described in equation (1) from the literature[5].

$$R_s mod = R_s cell + R_s tab + R_s tabext + R_s cables + R_s bus (1)$$

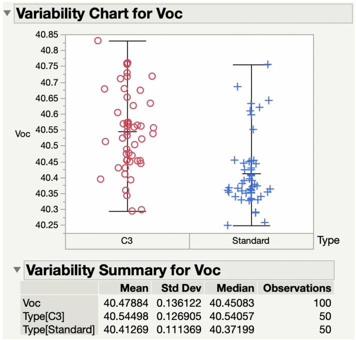
where $R_s$mod is the module series resistance, $R_s$cell is the cell series resistance, $R_s$tab is the tabbing resistance, $R_s$tabext is the tab extension between two cells resistance, $R_s$cables is the cable resistance, and $R_s$bus is the bus ribbon resistance. The cell series resistance is the only variable that changes between the two modules so the impact on the module FF is suppressed. Experimental data is shown in Figures 5, 6, and 7 where the module FF, Voc, and Power with binned solar cells having electrical parameters similar to Table 2. Figure 5 shows the difference in module fill factor supports little to no difference between the two groups of standard cells and Configurable Current Cells despite the lower cell fill factor. Figure 6 shows the difference in module voltage supports an >1mV per cell advantage for the Configurable Current Cells. Figure 7 shows an improved module power ~ 1 watt between two groups of 50 modules without any optimized binning for the same cell efficiency bin.



Variability Summary for FF

	Mean	Std Dev	Median	Observations
FF	0.792936	0.002922	0.792808	100
Type[C3]	0.792454	0.002737	0.792203	50
Type[Standard]	0.793419	0.003046	0.793477	50

5. Similar module fill factor for a 1mm gap on the front and rear metallization between busbars despite a lower cell fill factor.



Variability Summary for Voc

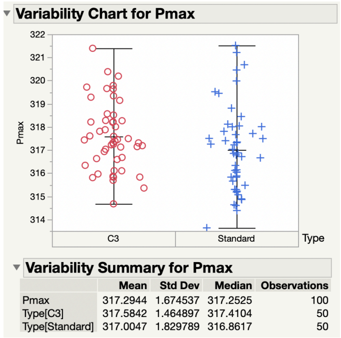
	Mean	Std Dev	Median	Observations
Voc	40.47884	0.136122	40.45083	100
Type[C3]	40.54498	0.126905	40.54057	50
Type[Standard]	40.41269	0.111369	40.37199	50

6. Improved module open circuit voltage by 0.14V for a 1mm gap on the front and rear metallization between busbars showing ~2 mV per cell improvement.

Incorporating the modified "H-Bar" pattern on the front and rear of a solar cell results in electrically semi-isolated busbars. During solar cell testing and sorting the electrical parameters are measured effectively in parallel so the behavior is similar to a metallization scheme with continuous metal on the front and rear of a solar cell which enables conventional testing/binning. Additional benefits within a module using alternative electrical architecture will be covered in a future publication for the Configurable Current Cell, C3, technology.

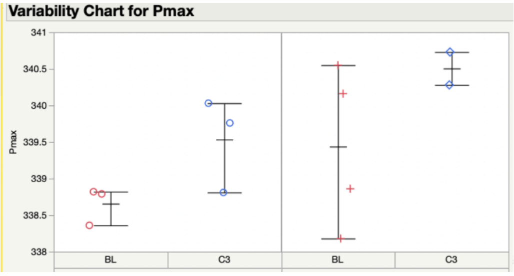
Experimental data using 5,000 standard "H-Bar" solar cells and 5,000 modified "H-Bar" pattern solar cells with 4 gaps, each 1mm, on a 5 busbar design were processed on Cz-Si

Passivated Emitter and Rear Contact (PERC) solar cells. The batch of solar cells were controlled to be processed on the same day, on the same material, by the same equipment with only a change of the metallization screens for the front and rear metal step. No process optimization was considered for the new front and rear metallization steps. Some results for multiple bins from an second module production line are shown in Figure 8 further supporting an improved cell to module ratio for the Configurable Current Cell technology module with similar efficiencies.



	Mean	Std Dev	Median	Observations
Pmax	317.2944	1.674537	317.2525	100
Type[C3]	317.5842	1.464897	317.4104	50
Type[Standard]	317.0047	1.829789	316.8617	50

7. Improved module power by ~1 watt for a 1mm gap on the front and rear metallization between busbars even thought the binned cell efficiency was equal.



8. Improved solar module power for two separate power bins with a 1 watt power increase for the modified "H-Bar" patterned solar cells.

IV. CONCLUSION

Modification of grid finger design has been shown to simultaneously reduce shading, increase open circuit voltage, increase short circuit current, and increase performance while reducing the amount of metal needed on the front and rear of a solar cell using the Configurable Current Cell technology. Even though the cell fill factor is reduced compared to a standard cell the module fill factor is maintained while keeping the improved open circuit voltage and increased short circuit current resulting in an improved cell to module ratio of ~0.25% for a similar efficiency standard "H-Bar" pattern design. Demonstrating an improved CTM from 97.5% to 97.75%. By optimizing the amount of metal needed on the emitter for each busbar using electrical constraints of the emitter and reducing the amount of metal needed on the rear side of a solar cell by using the constraints pertinent to the solar cell structure, a higher performance, at a lower cost using less material has been demonstrated. Just as the current design of busbars has changed to incorporate segmented busbars, floating busbars or no busbars where a multi-wire module is used, the design of grid fingers needs to also evolve to eliminate redundant or unnecessary function within the solar cell device. Using a technology like the Configurable Current Cell shown in this paper will provide additional methods to reduce the amount of silver or any metal needed to optimize the performance of a solar module by improving the cell to module ratio. In addition, C3 technology provides added flexibility in module circuitry that is discussed in future publications.

ACKNOWLEDGMENT *(Heading 5)*

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