Reduced Silver Consumption for Optimized Performance of Crystalline Silicon Photovoltaic Devices Using the Configurable Current Cell Electrical Architecture

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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. Improved solar cell and solar module performance metrics are increased while reducing the amount of metal needed per solar cell. 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 that includes a modified "H-Bar" metallization pattern shown in this paper will provide additional methods to reduce the amount of metal needed on the front and rear of a solar cell to optimize the performance of a solar module.**

Keywords— silver, grid finger shading, metallization, cell to module

I. INTRODUCTION (*HEADING 1*)

The continued reduction in cost of solar energy is significantly impacted by the amount of silver used in front and rear metal pastes for photovoltaic devices. 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 [1]. A number of publications in the photovoltaics industry site the need to reduce the silver consumption per cell, in fact, the International Technology Roadmap for Photovoltaics 2019 [2], reports the silver used per solar cell each year and forecasts half the amount of silver per cell by 2029. 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, and interdigitated back contact solar cells all use metal and silver is most common. The resulting "H-Bar" pattern has survived for decades for non interdigitated back contact cells.

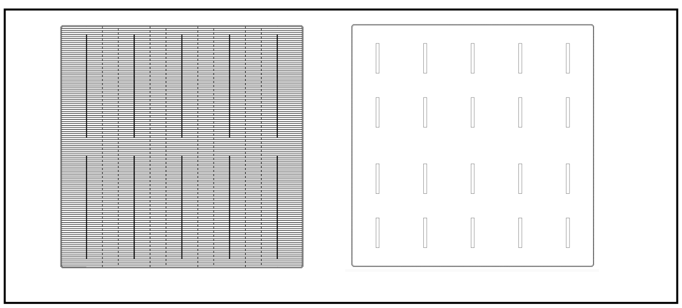
The most common solar module used in 2021 is the mono facial crystalline silicon with the "H-Bar" front silver pattern. The device parameters are continually evolving. The printed metal layers are tasked with making electrical connection with the emitter and back surface field (anode and cathode) while also conducting the power to the outside world. Another important metallization strategy is to balance the optical shading loss with electrical loss. Current industrial solar cells may have less than 5% silver shading. State of the art laboratory solar cells do not experience electrical conductivity issues like current crowding for devices where 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 solid rectangle that stretches the length of a solar cell to a 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. By changing the simple rectangular 2-D design of the busbar, the Jo-metal can be improved resulting in an increase in open circuit voltage. The edge interface shape can help remove stress from the edge of the crystalline silicon wafer. Solder pads for the solar cell and Lighted IV measurement pads can be aligned such that the amount of silver is minimized. 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 is made on fine line printing and penetration depth. 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. By changing the layout of the grid pattern, including the grid fingers and busbars, new metallization designs can better optimize the solar cell performance while reducing the silver required, when using the Configurable Current Cell (C3) technology [5]. By considering the solar cell device parameters, grid finger functionality can be thought of as performing two mechanism, first to extract electrical current after being absorbed and collected from the cell followed by being conducted to the bus bars for participation in a loaded circuit. Modification of the continuity of the metallization pattern along with slight changes to existing cell design parameters, a multiple PV device architecture is implemented on a single silicon wafer.

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.

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 of a mono facial solar cell and the corresponding rear side metallization 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 the opposite side surface field layer lowers the resistance of the bulk region and aids a more 3-D movement of collected photons. The front metal fingers are used to extract current from the body of the solar cell and transport the collected current to the bus bars for participation in an electrical circuit. The rear metallization also extracts the collected current, transports it the bus bars, and for devices structures based on PERC cells the creation of a high-low junction for surface passivation is also accomplished.



1. Standard "H-bar" front pattern with standard rear metallization pattern.

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 continuous 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, Rc, and while not significantly lowering the fill factor, FF. Maintaining the distance a collected photon needs to travel in order to reach a grid finger while considering the emitter, back surface field, and bulk material parameters can be used to limit any change to the device FF. Other device parameters like electric shadowing and optic shadowing must also be considered for metallization design concepts. Figure 2 shows a modified "H-Bar" pattern for the front and rear of a 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. The reduction in metal coverage also lowers the Jometal providing a potential boost in open circuit voltage. Equation (1), (2), and (3) shows the impact of $J_o$metal on open circuit voltage.

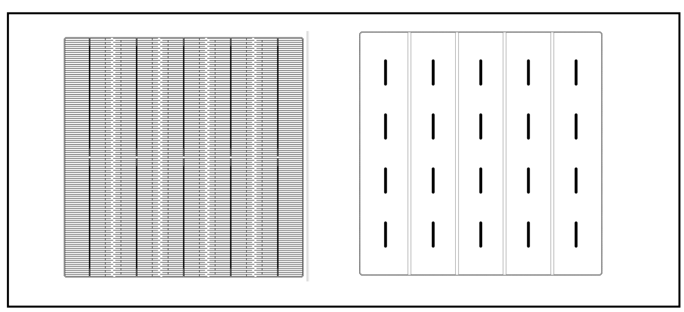
$$J_o = Joe + Job + J_o metal \quad (1)$$

$$J_o metal = J_o metalFr + J_o metalRr \quad (2)$$

where Joe and Job are the emitter and bulk recombination current, $J_o$metal is the recombination current from the metal/ silicon interface, $J_o$metalFr is the front metal recombination current, and $J_o$metal rear is the rear metal recombination current.

$$Voc = nkT/q(J_L/J_o + 1) \quad (3)$$

and n is the diode ideality factor, k is boltzmann's constant, JL is the photon current generated by incident light, and q is the charge. By reducing the $J_o$metal component the open circuit voltage will increase. The increase in photocurrent is proportional to the reduction in metal shading. Consider an "H-Bar" design where the non-continuous region or "gap" is on the order of 2mm for a 158.75mm square wafer and there are 120 grid fingers for a 5 busbar pattern. There would be 4 "gaps" each with a 2mm length multiplied by 120 grid lines. The four gaps would save a length of 960mm (or effectively 157.75/960 = 6.1 grid lines). This represents a savings of 5% for the metal grid fingers and a corresponding drop in $J_o$metal. Similarly, the rear side of the device should also employ a non-continuous metal grid or "H-Bar" pattern with a gap constrained by the bulk lifetime and surface passivation. The rear side metal could be reduced by a 3mm "gap" between each busbar which does not alter the current flow per busbar and saves 12mm of length on a 157.75mm paste deposition or 7.6% metal reduction. Provided passivation is properly maintained in the "gap" regions, any adverse impact to cell performance is either minimized or eliminated. If both "H-Bar" patterns are silver, the cost savings and metal reduction is more than doubled as in advanced n-type bifacial cells. In addition, the solar cell and solar module efficiency may also benefit through reduced optical shadowing, reduced electrical shadowing, and improved surface passivation.

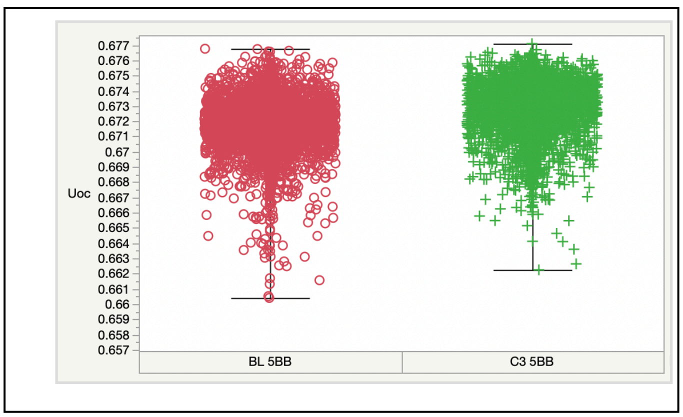


2. Modified "H-bar" front pattern with modified rear metallization pattern using so called Configurable Current Cell technology.

Incorporating the modified "H-Bar" pattern on the front and rear of a solar cell results in electrically semi-independent 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, however, current leakage between probes is sometimes present without an isolation resistor. Additional benefits within a module electrical architecture will be covered in a future publication for the Configurable Current Cell, C3, technology exploring the advantages of the electrically semi-independent busbar giving rise to multiple photovoltaic devices on a single wafer.

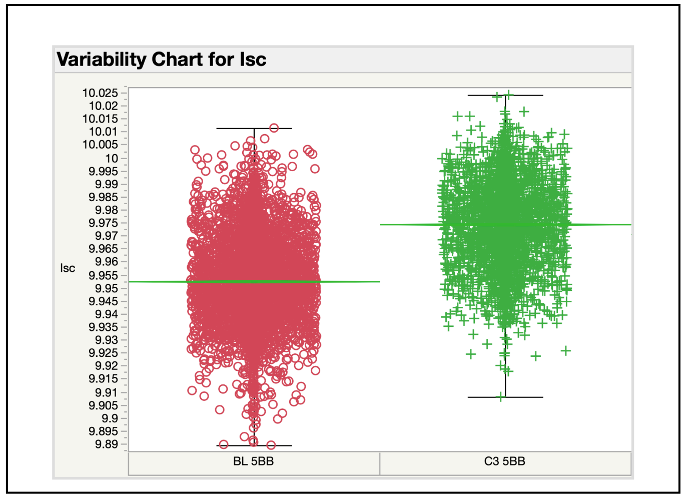
III. Application and Results

Using a modified metallization design similar to Figure 2 on an industrial production line was possible because no additional process equipment was needed. Both solar cell processing and solar module processing are compatible with a simple metallization design change provided proper care is taken to be compatible with the existing equipment, such as in Figure 2. 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.

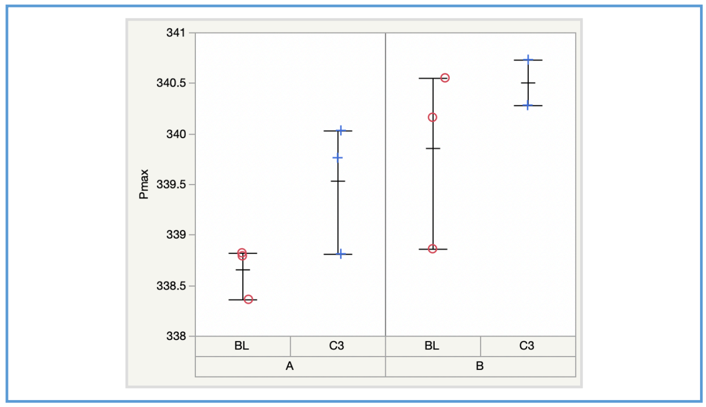


3. Improved solar cell open circuit voltage by 1.0 mV for a 1mm gap on the front and rear metallization between busbars from 672.0 mV to 673.0 mV.

Figures 3 and 4 show cell data supporting a 1.0 mV increase in open circuit voltage and 0.02 ampere improvement in short circuit current for the samples with the modified "H-Bar" pattern with gaps. Figure 5 shows the improved module power of more than 1 watt for a "G1" sized 60 cell panel from a similar bin for standard "H-Bar" and modified "H-Bar" metallization designs with Configurable Current Cell technology. Module FF was maintained resulting in improved cell to module power ratio, discussed in greater detail in a future publication. Standard modules were fabricated using the same wafers and reproduced the improved current and voltage while keeping the fill factor equal to the standard "H-Bar" design in the finished module.



4. Improved solar cell short circuit current by 0.02 ampere for a 1mm gap on the front and rear metallization with 110 grid fingers.



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

IV. Modeling

Using the same modified "H-Bar" metallization design similar to Figure 2 for the front silver and rear aluminum on a 9 bus bar bifacial PERC cell is simulated using a 2 dimensional modeling software, Griddler. Standard device parameters for bifacial PERC cells were downloaded directly from the Griddler website. Figure A shows the cell efficiency data for a range of rear aluminum gap sizes for a fixed 1mm front silver gap. The cell efficiency is maintained or improved over the 0mm gap baseline front and rear (no gaps) for a range of rear side gaps between 1mm - 4mm before a significant drop observed for a 5mm rear gap.

V. Impact

Consider a 9 bus bar bifacial PERC cell designed with the Configurable Current Cell technology using a 1mm front silver gap and a 2mm rear Aluminum gap. Using some common production line values and 25 GW's of capacity, the reduction in cost per cell plus the use of less silver on the front and less

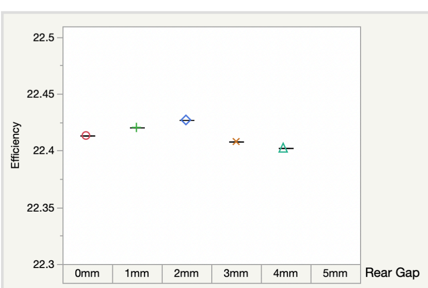
Aluminum on the rear can be estimated using a few more assumptions. See Table 1 for a example scenario reduction.

Assumptions:			Ag Price ($/kg)	$870.00
Technology	Bifi PERC		Al Price ($/kg)	$11.00
# of Bus Bars	9		"G1" Cell Efficiency	22.50%
# Fr Ag Grid Finger	120		G1 Watts/wafer	5.67
# Rr Al Grid Finger	150		# G1 wafers/GW	176261925.2
Length of Grid Finger (mm)	157.5		Bifi PERC GWs	25
Front Gap (mm)	1		Ag/Wafer (mg)	0.05
Rear Gap (mm)	2		Al/Wafer (mg)	0.15
Total Front Grid Length	18900		Silver Saved (kg)	11191.23335
Total Rear Grid Length	23625		Silver Saved ($)	$9,736,373.01
Front Grid Reduction (%)	5.1%		Aluminum Saved (kg)	67147.40008
Rear Grid Reduction (%)	10.2%		Aluminum Saved ($)	$738,621.40

Table 1. Metal reduction for the front and rear for a solar cell

VI. CONCLUSION

Modification of grid finger design has been shown to simultaneously reduce optical 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. 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. Efficient current collection and sufficient electrical current transport should be separately optimized. 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. Two dimensional and three dimensional current transport within the bulk, emitter, and surface field regions should be further optimized to increase performance and reduce screen printed metallization. In addition, added flexibility in module circuitry can be realized.



Variability Summary for Efficiency

	Mean	Std Dev	Maximum	Observations
Efficiency	21.84915	1.383981	22.42695	6
Rear Gap[0mm]	22.41324	.	22.41324	1
Rear Gap[1mm]	22.42035	.	22.42035	1
Rear Gap[2mm]	22.42695	.	22.42695	1
Rear Gap[3mm]	22.40793	.	22.40793	1
Rear Gap[4mm]	22.40224	.	22.40224	1
Rear Gap[5mm]	19.02416	.	19.02416	1

6. Griddler modeled results for a fixed cell parameters for PERC bifacial 9BB solar cells with a modified "H-Bar" design using the C3 technology demonstrating stable efficiency for 1mm front gap and a varying rear gap of 1mm - 4mm before losing efficiency at 5mm.

ACKNOWLEDGMENT *(Heading 5)*

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