Silver Contact Grid: Inferred Contact Resistivity and Cost Minimization in 19% Silicon Solar Cells

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Abstract—The analysis of silicon solar cell contacts having an H-bar front grid pattern is extended by enabling the contact resistivity to be inferred from the measurement of total series resistance and the determination of six individual components of series resistance. Analysis of the contact system was completed for a representative 19% cell fabricated from a 156-mm pseudosquare p-Cz wafer using standard production processes, including phosphorus ion implantation, thermal oxide surface passivation, silicon nitride deposition, and screen-printing and firing of front silver gridlines and busbars, back silver soldering pads, and back aluminum contact. Gridline width was measured to be 80 μm after firing, with an average thickness of 7.4 μm and an effective resistivity of 4.7 $\mu\Omega\cdot$cm. Contact resistivity to the uniform 91 $\Omega/\square$ emitter was inferred to be 5.3 m$\Omega\cdot$cm^2 from the total series resistance and its components. Using these values, gridline spacing was optimized for maximum efficiency (1.7 mm, 91 lines, 19.1%, \$0.040/W) or minimum silver cost (2.1 mm, 74 lines, 19.0%, \$0.038/W). The analysis methodology was further applied to examine the impact of gridline width and silver pricing on cell efficiency and incremental cost. Such analysis can serve as a guideline for future contact system designs when the cost of silver changes or when printing technology allows narrower lines.

Index Terms—Contacts, silicon, silver, solar energy.

I. INTRODUCTION

NEXT to the silicon wafer itself, the contact materials are the most costly element of crystalline silicon solar cells in production today. The most common materials are silver for the front grid and back soldering pads, and aluminum for the back contact. These are usually deposited by screen printing and then co-fired in a belt furnace. Silver is a popular choice for the front grid because of its high electrical conductivity, solderability, and long-term stability. Silver particles can readily be incorporated into a screen-printable paste along with proprietary components, such as glass frit, binders, and solvents. These enable the printing of narrow, yet reasonably tall lines, which can be fired through front dielectric layers to contact the doped front silicon surface of the solar cell with low contact resistance. However, silver is also a costly material (approximately \$1/g), and therefore efforts are made to minimize its use. A front grid system is often designed to maximize cell efficiency, with grid shadowing balanced against ohmic losses, but it is perhaps more important from a commercial viewpoint to minimize the incremental cost (Δ\$/W) of the silver grid. Toward that end, this paper has the following objectives.

1) Provide a complete and updated set of expressions to calculate the normalized components of series resistance ($\Omega\cdot$cm^2) in a modern large-area silicon solar cell with an "H-bar" front contact pattern of parallel grid lines and perpendicular busbars.
2) Provide a means for inferring silver/silicon contact resistivity without having to resort to a current transfer length method (TLM) measurement.
3) Apply the analysis techniques to cells fabricated with state-of-the-art production processes to optimize the grid pattern for minimum incremental cost (Δ\$/W).
4) Calculate, based on measured cell values, the optimal gridline spacing required for maximum efficiency or for minimum Δ\$/W with gridline width and silver cost as parameters.

Analysis is carried out with cells fabricated using standard production processes at Suniva. Cells begin with a textured (both sides) p-Cz wafer and feature a uniform ion-implanted phosphorus front emitter, thermal silicon dioxide surface passivation, silicon nitride antireflective coating, aluminum back surface field, front silver grid, and back silver soldering pads.

II. EXPRESSIONS FOR SERIES RESISTANCE COMPONENTS

An early treatment of the front contact for large area (100-mm square) solar cells is given in [1]. Of the four grid patterns considered, the one with the lowest total power loss was an H-bar design with parallel grid lines and four orthogonal busbars. The pattern had a 6.1% shadowing loss and a 1.4% ohmic ($J_{mp}^2 * R_{series}$) loss for a total loss of 7.5%. These values were obtained with copper grid lines having a width of 75 μm, a thickness of 10 μm, and a spacing of 2.0 mm. The four busbars were copper wires, each 0.644 mm in diameter. The copper grid contacted an emitter layer having 35 $\Omega/\square$ sheet resistance, and the base was 200 μm thick with 1 $\Omega\cdot$cm resistivity. Other treatments of contact systems can be found in [2]–[4], including consideration of an H-bar design with an arbitrary number of busbars.

Fig. 1.   Diagram of rectangular H-bar pattern with three busbars. Subcell used for analysis has length $a = s/(2n_{bb}) = s/6$ and width $2nb$, where $2b$ is center-to-center spacing between gridlines, and $2nb$ is the spacing between current pick-up probes in the cell tester.

Fig. 2.   Three-dimensional microscope image of a screen-printed silver gridline showing nonuniformity in both thickness and width, with peak thickness of 22 μm (Suniva cell LDE-G3-17).

Basic expressions for calculating the power loss from different regions of the solar cell are derived in [5] for a "comb" grid pattern (grid lines perpendicular to a single busbar). Building on these expressions, the components of series resistance (normalized to unit cell area) are developed in [6] for a two-bus H-bar pattern. This paper treats a more general H-bar pattern applied to a rectangular cell with any number of busbars, and also includes an updated expression for the series resistance component associated with the front busbar. Shown in Fig. 1, for example, is a rectangular cell with three busbars, typical of cells currently in production. The key construct is an elementary subcell "a" units long and "$2nb$" units wide, with "n" grid lines having center-to-center spacing of "$2b$" units. Current pick-up probes in a cell tester are assumed to have a spacing equal to the subcell width ($2nb$). For a full cell "s" units long, the length of the subcell (a) is $s/(2n_{bb})$, where n_{bb} is the number of busbars. For example, a production cell 156 mm long with three busbars will be represented by a subcell of length 26 mm. The arrangement in Fig. 1 shows five gridlines per subcell, which is representative for typical current probe separation. However, it should be noted that the formalism is accurate, even if n is not an integer.

There is usually a disconnect between analytical grid design and actual implementation on a cell. This is because the analysis assumes uniform gridlines having constant width and thickness (rectangular cross-section) and a constant and known resistivity. In practice, the cross section is not rectangular, and neither the width nor the thickness is constant—particularly for screen-printed lines. This is shown in Fig. 2 by the 3-D image of a grid line, taken with a digital microscope (Keyence VHX-600). The observed undulations result from paste being squeezed through the mesh of wires in the screen. Furthermore, the resistivity of the grid line is not necessarily the handbook value for bulk material. For example, a screen-printed silver line is made up of silver particles which are sintered together. Proprietary materials in the silver paste (organic binders, glass frit) may introduce some resistance between the sintered silver particles, thereby increasing the effective resistivity of the line. In addition, small voids exist within the line—again increasing its effective resistivity.
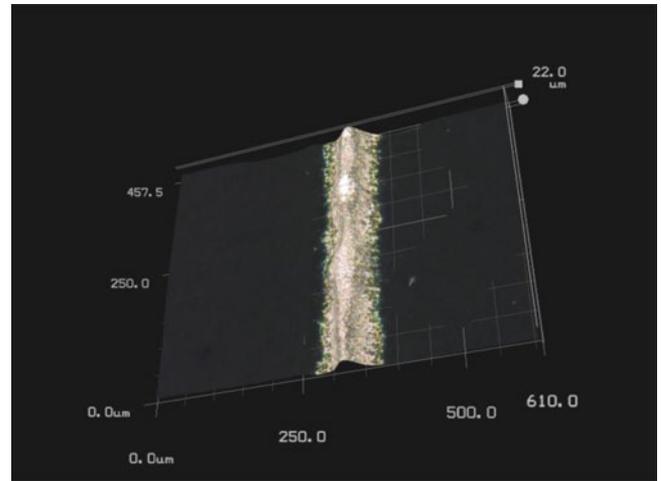
In the analysis described here, complications associated with nonuniformity of gridline width w, thickness t, and resistivity ρ are avoided by recognizing that the individual values of w, t, and ρ are not needed, but only the combination $\rho/(tw)$ is needed. This combination can be easily determined empirically from a cell by the measurement of resistance between adjacent busbars, which is a measurement of the parallel combination of all n_{gl} gridline segments between the two busbars. The measurement is called "busbar-to-busbar resistance" (BBR) and provides an effective value of the required combination of $\rho/(tw)$, averaged over all n_{gl} gridlines. A similar value for the combination of parameters required for the busbar $\rho/(tw)$ is obtained by the measurement of the resistance of the full length of the physical busbar on the cell. Here, recognize that w' is the width of the busbar in the subcell, which is half the width of the physical busbar of the cell, as shown in Fig. 1. Thus, two simple measurements on the finished cell (BBR and busbar resistance) provide the information needed to calculate the series resistance components associated with the gridlines and with the front busbar. No corrections are made to these measured values for front contact resistance or emitter sheet resistance, as such corrections alter the measured resistance values of the metal gridlines and busbars insignificantly. The individual components of series resistance, normalized to unit area, can now be quantified with convenient units of $\Omega \cdot \text{cm}^2$.

The expressions used to calculate six components of series resistance [5], [6] are summarized in Table I. R_{bus} is the resistance of the front busbar measured over its full length s' on the finished cell. The expression for r_s(front busbar) differs from [6] in that n^2 is replaced by $(n+1)(n+2)$. This accounts for the fact that current enters the busbar in discrete "lumps," rather than continuously (n^2) as assumed in [6], since each gridline delivers a quantity of current, which then flows along the busbar until it is joined by another "lump" from the next gridline. ρ_w and t_w are the resistivity and thickness of the wafer

TABLE I
EXPRESSIONS FOR CALCULATING NORMALIZED SERIES RESISTANCE COMPONENTS ($\Omega \cdot cm^2$)

Component	Expression (Ω-cm^2)
Front Busbar	$r_s(\text{front busbar}) = (1/3)a(n+1)(n+2)b^2\rho/(tw') = (1/3)a(n+1)(n+2)b^2(2R_{bus}/s')$
Gridlines	$r_s(\text{gridline}) = (2/3)a^2b\rho/(tw) = (1/3)(abn_{gl})BBR$
Front Sheet	$r_s(\text{sheet}) = (1/3)b^2R_{sheet}$
Substrate	$r_s(\text{substrate}) = \rho_w t_w$
Back Metal	$r_s(\text{back metal}) = (1/3)a^2R_{sheet}(\text{metal})$
Back Busbar	$r_s(\text{back busbar}) = r_s(\text{front busbar})*(\text{width front busbar/width back busbar})$

TABLE II
MEASURED PARAMETERS FOR CONTACT SYSTEM (CELL LDE2-G3-17)

Parameter	Description	Value
s	cell horizontal side length	156 mm
s′	cell vertical side length	156 mm
n_{bb}	number of bus bars	3
a	length of gridlines in subcell	26 mm
2b	grid line spacing	2.10 mm
n	number of gridlines per subcell	5
n_{gl}	total number of gridlines in full cell	74
w	width of gridline	80 μm
2w′	width of front busbar on cell	1.5 mm
R_{sheet}	sheet resistance of front implanted silicon layer	91 Ω/□
$R_{sheet}(\text{metal})$	sheet resistance of back metal	7.72 mΩ/□
ρ_w	wafer resistivity	2 Ω-cm
t_w	wafer thickness (after texturing)	180 μm
J_{sc}	short circuit current density measured by cell tester	37.80 mA/cm^2
V_{oc}	open circuit voltage measured by cell tester	0.6410 V
FF	fill factor measured by cell tester	0.7869
Efficiency	efficiency measured by cell tester	19.07%
PFF	pseudo fill factor measured by Suns-Voc	0.830
BBR	busbar-to-busbar resistance	0.056 Ω
$R_{bus}(\text{front})$	front busbar resistance	0.1048 Ω
$W_{\text{back busbar}}$	width of back busbar (soldering pad)	4.0 mm
$\Delta FF/r_s$	fill factor sensitivity factor (FF loss relative to PFF)	0.0489/Ω-cm^2

(substrate). $R_{\text{sheet}}(\text{metal})$ refers to the sheet resistance of the back metal contact (typically fired aluminum) and represents the loss associated with current traveling to the back busbars. Since the resistance of the back busbar is difficult to measure in a completed cell because of the overlapping aluminum, the (small) $r_s(\text{back busbar})$ component is approximated by scaling $r_s(\text{front busbar})$ by busbar widths.

III. INFERRED CONTACT RESISTANCE COMPONENT OF SERIES RESISTANCE FROM REPRESENTATIVE CELL DATA

Experience has shown that the cell total series resistance, along with the six components of series resistance given in Table I, can be calculated quite accurately and precisely. The total series resistance is determined from the pseudofill factor (PFF), as given by a Suns–V_{oc} measurement [7], and the cell fill factor (FF) according to the method in [8] as

$$r_s(\text{total}) = [V_{oc}/J_{sc}][(PFF - FF)/PFF]. \quad (1)$$

Alternatively, $r_s(\text{total})$ can be determined from measurements of the cell *I–V* curves at two different light intensities.

The component of series resistance associated with the front contact resistance can then be inferred by subtracting the sum of the components from the total series resistance. Contact resistivity can, in turn, be determined by multiplying this inferred component by the fractional area covered by the gridlines (f)

$$r_s(\text{contact}) = r_s(\text{total})$$
$$- [r_s(\text{front busbar}) + r_s(\text{gridline}) + r_s(\text{sheet})$$
$$+ r_s(\text{substrate}) + r_s(\text{back metal})$$
$$+ r_s(\text{back busbar})] \quad (2)$$
$$\rho_c = [f][r_s(\text{contact})]. \quad (3)$$

Results are summarized in Tables II and III for a 156-mm pseudosquare (239 cm^2 area) Suniva cell with J_{sc} of 37.80 mA/cm^2, V_{oc} of 0.6410 V, FF of 0.7869, and efficiency of 19.07% (stabilized). A photograph of such a cell is given in Fig. 3. Note that linewidth is 80 μm, and contact is made

TABLE III
SERIES RESISTANCE COMPONENTS AND INFERRED CONTACT RESISTIVITY (CELL LDE2-G3-17)

Component	Description	Value
r_s(total)	total series resistance of cell (from PFF and FF)	0.8806 Ω-cm^2
r_s(front busbar)	front busbar component	0.0030 Ω-cm^2
r_s(gridline)	gridline component	0.3745 Ω-cm^2
r_s(sheet)	front sheet component	0.3281 Ω-cm^2
r_s(substrate)	substrate component	0.0360 Ω-cm^2
r_s(back metal)	back metal component	0.0174 Ω-cm^2
r_s(back busbar)	back busbar component	0.0011 Ω-cm^2
$\sum r_s$(components)	(back metal and back busbar not included)	0.7416 Ω-cm^2
r_s(contact)	inferred front contact resistance component	0.1390 Ω-cm^2
f	fractional area covered by gridlines	0.0379
ρ_c	contact resistivity from inferred r_s(contact)	5.27 mΩ-cm^2

Fig. 3. Photograph of 156-mm pseudosquare cell with grid pattern of the type analyzed.

Fig. 4. Resistance data for determining contact resistivity (3.51 mΩ-cm^2) and sheet resistance (88.9 Ω/$\square$) directly from a TLM-type pattern for 19.12% cell.

to a 91 Ω/$\square$ phosphorus-doped emitter (ion implanted and annealed) with a resulting contact resistivity ρ_c of 5.3 mΩ·cm^2. The phosphorous surface doping concentration is estimated to be 1.6E20 P/cm^3 based on dopant profiles obtained under similar implant and anneal conditions and measured by the electrochemical C–V technique. Since the cell FF was determined with a tester having a full metal stage rather than back current probes, r_s(back metal) and r_s(back busbar) do not contribute to the total series resistance measured, and so are not included in the calculation of inferred r_s(contact). The largest components of series resistance are those from the gridlines, front sheet, and front contact. Overall, shadowing was 6.68% of the cell area and accounted for a power loss of 1.19 mW/cm^2. Ohmic losses were 0.95 mW/cm^2 or 4.98% of the 19.07% cell efficiency.

The value of ρ_c was also inferred for two other similar cells (efficiency of 19.01% and 19.12%) to be 1.08 and 3.53 mΩ·cm^2, respectively. The average and standard deviation of ρ_c for all three cells is then 3.3 $\pm$ 2.1 mΩ·cm^2. Note that (3) is valid provided $w/2 < L_T$, where L_T is the current transfer length given by ($\sqrt{\rho_c R_{sheet}}$) [5]. This requirement is met for the average contact resistivity (40 μm < 55 μm).

In order to check the validity of the inferred contact resistivity, a TLM-like pattern was laser cut from the 19.12% cell, which had an inferred ρ_c of 3.53 mΩ·cm^2. The test pattern was a strip, 1.00 cm wide, cut perpendicular to the gridlines. The test strip has the appearance of a ladder, with the gridline segments forming the rungs of the ladder and acting as the contact bars in a TLM pattern. Center-to-center spacing of the gridlines was 0.208 cm. As described in [6], the resistance is measured from a reference line to lines 1, 2, 3, 4, and 5 spacings removed from that reference line. A plot of such measured resistances as a function of gridline separation is given in Fig. 4, along with the equation for the fitted line. Since the width of the test pattern is 1.00 cm, the slope of the line gives the emitter sheet resistance as 88.9 Ω/$\square$. The intercept (0.867 Ω) represents the contact resistance for two bars or gridlines. With the gridline width measured as 81 μm and length as 1.00 cm, the contact resistivity measured directly by this TLM-ladder method is given as follows:

$$\rho_c = \tfrac{1}{2} * 0.867\,\Omega * 0.0081\,\text{cm} * 1.00\,\text{cm} = 3.51\,\text{m}\Omega \cdot \text{cm}^2. \tag{4}$$

This direct measurement of ρ_c (3.51 mΩ·cm^2) agrees remarkably well with the inferred value (3.53 mΩ·cm^2)—in fact, considerably better than an error analysis would indicate.

It should be appreciated that the inferred r_s(contact) of (2) is small compared with r_s(total) in a well-designed cell, and is calculated based on a number of measured parameters, each of which has an uncertainty (error). An error analysis was carried out based on standard deviations from five to ten measurements of the required parameters (except for ρ_w), according to [9]. The parameters used, along with their standard deviations, are: V_{oc} of 0.6410 ± 0.00012 V, J_{sc} of 37.80 ± 0.011 mA/cm^2, FF of 0.7869 ± 0.00126, PFF of 0.830 ± 0.00045, BBR of 0.056 ± 0.00142 Ω, R_{sheet} of 91 ± 3.89 Ω/□, and ρ_w of 2 ± 1 Ω·cm. Equations (1) and (2) then yielded a value of r_s(contact) of 0.139 ± 0.037 Ω·cm^2, or 0.139 Ω·cm^2 ± 27%. Contributions to the uncertainty were comparable (within a factor of 3) from the cell parameters of (1), BBR, R_{sheet}, and ρ_w. Allowing a w value of 80 ± 10 μm to propagate through f, ρ_c is determined from (3) to be 5.27 ± 1.55 mΩ·cm^2, or 5.27 mΩ·cm^2 ± 29%. Thus, the error analysis suggests the inferred contact resistivity is valid to within ± 1.55 mΩ·cm^2.

IV. OPTIMIZING GRIDLINE SPACING FOR MAXIMUM EFFICIENCY OR FOR MINIMUM COST

With material and geometric contact properties having been measured for a real cell fabricated with current technology, it is now possible to optimize gridline spacing to either maximize efficiency or minimize incremental cost (Δ$/W) of the front silver grid. Recall that measurements from the previous section indicated a postfiring silver gridline width of 80 μm. By knowing the weight of the silver paste used to print the front contact (gridlines and busbars) and the fraction of the paste weight attributable to silver (typically 85%), the average thickness of the printed silver is calculated to be 7.4 μm. By further knowing the BBR value, the effective resistivity of the printed silver gridlines is calculated to be 4.7 μΩ·cm (three times the bulk value of 1.59 μΩ·cm). The gridline material property (effective resistivity) and geometrical properties (width and average thickness), which have been demonstrated for current screen-printing technology and silver paste composition, remain constant as the spacing between gridlines is varied in an optimization calculation, as does the emitter sheet resistance (91 Ω/□) and the associated contact resistivity (5.3 mΩ·cm^2).

The results are given in Fig. 5. For these calculations, the cost of the silver paste is assumed to be $1/g, representative of current prices which are dominated by the cost of silver. The cost axis of Fig. 5 (Δ$/W) is associated with the front silver contact system only, and takes into account the cost of the material (silver paste) and the distribution of that material in the contact pattern (number of gridlines and busbars). Fig. 5 indicates that the minimum cost of the front silver contact is $0.038/W at an efficiency of 19.0% with a line spacing of 0.21 cm (74 lines), while the maximum efficiency is 19.1% at a cost of $0.040/W with a line spacing of 0.17 cm (91 lines). Note that the cell analyzed in the previous section has 74 lines, which is consistent with a contact system designed to minimize the incremental cost
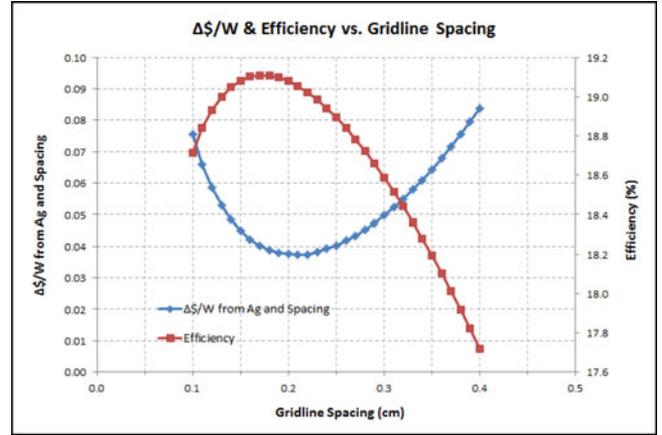
Fig. 5.   Plot of calculations to determine gridline spacing to maximize efficiency (0.17 cm, 91 lines) or minimize cost (0.21 cm, 74 lines). Gridline width, thickness, and resistivity are held constant at 80 μm, 7.4 μm, and 4.7 μΩ·cm in the calculations. Cost of silver paste is assumed to be $1/g.

per Watt. This analysis shows that a marginally higher efficiency (0.1% absolute) can be obtained at an increased expense of $0.002/W for the additional silver material. Although higher efficiency is desirable, and can sometimes command a premium price, it is unlikely that the market would be willing to pay an extra $0.002/W for an added 0.1% in absolute efficiency.

In the efficiency calculation for Fig. 5, the impact of gridline spacing on FF J_{sc} and V_{oc} is taken into account. As this spacing increases, FF decreases by virtue of increased series resistance, while J_{sc} increases because of reduced shadowing. V_{oc} increases with increased spacing because of reduced recombination at the overall metal/silicon interface. As described in [10]

$$J_0 = J_{0b} + (f)(J_{0e-\mathrm{met}}) + (1-f)(J_{0e-n+}) \qquad (5)$$

where J_0 is the total reverse saturation current density, f is the fraction of the cell surface covered with gridlines (e.g., 0.0379 at 2.10-mm spacing), $J_{0e-\mathrm{met}}$ is the J_0 component associated with the metallized emitter surface and its underlying n$^+$ region (taken to be 1500 fA/cm^2 as a representative value from [10]), J_{0e-n+} is the J_0 component associated with the unmetallized emitter surface and its underlying n$^+$ region (taken to be 60 fA/cm^2 from Suniva measurements), and J_{0b} is the J_0 component associated with the full base, including the fully metallized back surface field region (taken to be 450 fA/cm^2 based on Suniva measurements and on [11]).

In order to place cell performance on a firm footing, another p-base cell fabricated according to the process outlined above was sent to Fraunhofer ISE CalLab for certification. Results for this 156-mm pseudosquare cell are given in Fig. 6, showing a confirmed stabilized efficiency of 19.05% with I_{sc} of 9.019 A (J_{sc} of 37.67 mA/cm^2), V_{oc} of 0.6397 V, and FF of 0.7903. This cell had 74 gridlines and was fabricated according to the minimum silver cost guidelines.

V. CONSIDERATION OF FUTURE TRENDS

The methodology that has been developed can be applied to examine the impact of the cost of silver paste and gridline
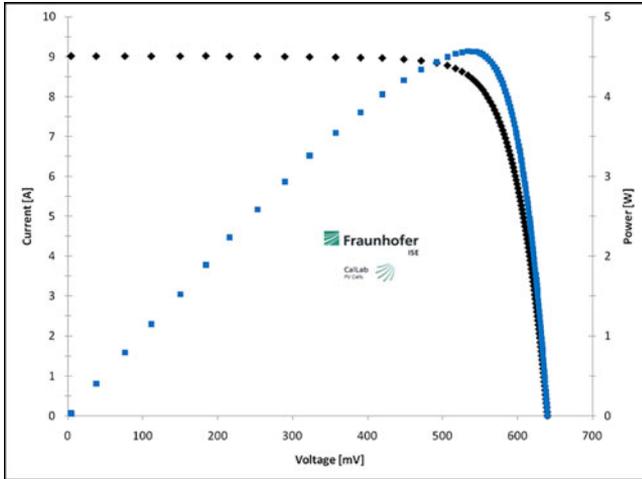
Fig. 6.   Fraunhofer-certified 19.05% cell (Suniva cell SUN_SEL_8).
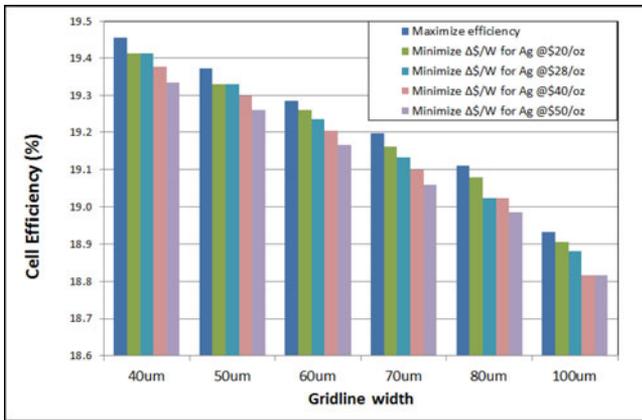
Fig. 7.   Calculated cell efficiency resulting from optimizing gridline spacing to either maximize efficiency or minimize silver cost, with silver cost and gridline width as parameters. (Troy Ounce is abbreviated as oz.)
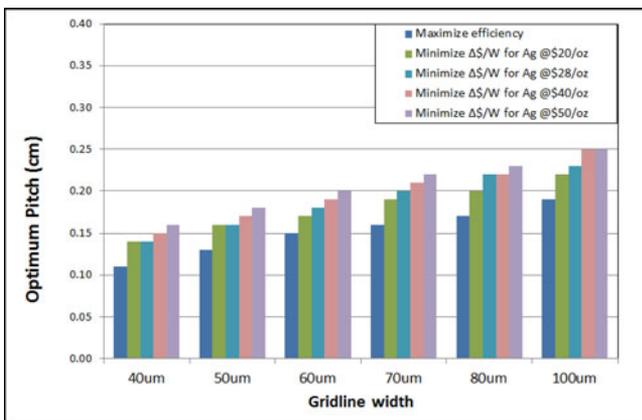
Fig. 8.   Calculated gridline spacing to either maximize efficiency or minimize silver cost with silver cost and gridline width as parameters. (Troy Ounce is abbreviated as oz.)

width on cell efficiency and on gridline spacing. Figs. 7 and 8 summarize the results of one such analysis. In all cases, the values of average gridline thickness (7.4 μm), gridline width (80 μm), effective gridline resistivity (4.7 $\mu\Omega\cdot$cm), contact resistivity (5.3 m$\Omega\cdot$cm^2), and emitter sheet resistance (91 $\Omega/\square$)

that were extracted from measurements and analysis of a fabricated cell were used. In Figs. 7 and 8, Troy Ounce is abbreviated as oz, where 1 oz is equivalent to 31.1 g. Note that as silver prices go up, efficiency decreases (see Fig. 7) and gridline spacing increases (see Fig. 8) in order to minimize $\Delta\$/W$. Maximum efficiency is independent of silver cost and favors narrow gridlines with small spacing, as expected.

VI. CONCLUSION

From this paper, the following conclusions can be drawn.

1) Accurate analysis of the gridline loss component in an H-bar contact grid system is greatly facilitated by a simple measurement of busbar-to-busbar resistance.
2) The proper treatment of current arriving at a busbar from discrete gridlines gives a series resistance component for the busbar, which is a factor of $[(n+1)(n+2)]/n^2$ larger than that given assuming a continuous flow of current into the busbar, where n is the number of gridlines per current probe.
3) Contact resistivity of the front silver contact can be inferred from the measurement of pseudo FF (Suns–V_{oc}), cell J_{sc}, V_{oc}, and FF (I–V curve) and the determination of six components of series resistance along with the fractional area covered—without resorting to a TLM measurement.
4) Error analysis suggests inferred contact resistivity is accurate to within approximately $\pm$ 1.6 m$\Omega\cdot$cm^2.
5) Current screen-printing technology and silver paste allow for a contact resistivity of approximately 3.3 m$\Omega\cdot$cm^2 when contacting a 90 $\Omega/\square$ ion implanted/annealed phosphorus-doped emitter.
6) Current screen-printing technology and silver paste cost indicate gridline spacing of 1.7 mm to maximize efficiency and 2.1 mm to minimize silver cost.
7) Guidance regarding optimum gridline spacing (screen design), which follows from future silver price changes or lifting of technological limits (gridline width) is available through a contact analysis, as described.
8) Contact analysis helps to enable full-sized (239 cm^2) production-worthy cells fabricated from p-Cz silicon substrates with efficiencies in excess of 19%, as confirmed by Fraunhofer ISE CalLab.

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