DETERMINING COMPONENTS OF SERIES RESISTANCE FROM MEASUREMENTS ON A FINISHED CELL

D. L. Meier, E. A. Good, R. A. Garcia. B. L. Bingham, S. Yamanaka, V. Chandrasekaran and C. Bucher
Solar Power Industries, Inc., 13 Airport Road, Belle Vernon, PA 15012 USA

ABSTRACT

Detailed expressions are given for computing the components of series resistance for a cell with a common contact pattern of parallel, equally-spaced gridlines which are perpendicular to two or more busbars. Front busbars and gridlines, contact resistance, emitter sheet, substrate, back metal and back busbars are all considered. No detailed thickness profiles are needed for any feature, only basic lengths and separations along with four-point resistance measurements. Results are given for a two-bus 15 cm square multicrystalline silicon cell having an efficiency of 15.0%. The total series resistance is 1.04 Ω-cm^2, dominated by the gridline contribution. The addition of a third busbar is calculated to result in an increase in FF of 0.018, corresponding to an increase of 0.36% in absolute efficiency. A method for providing a coarse map of pseudo contact resistance for a finished cell, using only a four-point probe, is also introduced.

INTRODUCTION

The fill factor of a solar cell is determined by its series resistance, shunt resistance, and diode ideality factor. Overall, the series resistance is determined by a host of individual resistance contributions: front busbars, front gridlines, interface between front contact metal and silicon, emitter sheet, bulk substrate, back metal, and back busbars. When attempting to improve the performance of a cell, it is important to know the magnitude of all components of the total series resistance. For example, narrower gridlines are desirable to reduce shadowing losses, but narrowing the lines leads to increased resistance associated with the front grid (less metal to carry the current) and the contact interface (less area of contact). Similarly, one may wish to raise the sheet resistance of the emitter layer in an effort to increase cell current (reduce emitter "dead layer"), but this comes at the expense of higher resistance associated with the emitter layer and with the contact interface. It is most direct to determine the various series resistance components from the finished cell itself, rather than from test patterns on witness wafers or from calculated values based on assumed material properties (e.g., resistivity of screen-printed gridlines) and on assumed geometrical values (e.g., thickness and width of gridlines). In that spirit this paper aims to:

1. Describe a method by which all components of series resistance can be determined from simple measurements on the cell itself;
2. Provide expressions for evaluating normalized series resistance components (and associated fill factor loss) for common front grid and back metallization patterns;
3. Introduce a technique by which the contact resistance associated with the front grid can be (coarsely) mapped non-destructively from the cell itself in arbitrary units, with no special test pattern.

APPROACH

This method assumes the common front grid pattern of parallel gridlines orthogonal to two or more parallel busbars, as shown in Fig. 1 for a square cell. Circles represent the points where probes contact the busbar during standard cell performance testing. Part of the challenge is to relate this common contact pattern to a simpler pattern for which series resistance expressions have already been developed [1]. In recognizing the path by which photocurrent generated within the cell travels to the test probes in contact with the busbar on the front (and also the busbar on the back), it is possible to make this relation. The left lightly-shaded area of Fig. 1 shows that elementary section of the cell where current is collected by a group of gridlines and fed via the busbar to a single test probe. The full contact system for the entire cell can be obtained by replicating this elementary section. Note that the length of the gridlines associated with the elementary section is one-fourth the width of the cell, and the width of the "busbar" of the elementary section is half the width of the cell busbar. The number of gridlines in the elementary section depends on the current probe separation in the particular test setup.

RESULTS

For the 15 cm square multicrystalline cells typically produced by Solar Power Industries and tested with current pick-up probes spaced 1.30 cm (2nb) apart, the elementary section of Fig. 1 has 5 (n) gridlines, each 3.75 cm (a) long and spaced on 0.26 cm (2b) centers. The resistivity of the front metal (ρ_f), along with its effective thickness (t), gridline width (w), and busbar width (w') need not be known individually, but only in certain combinations which can be evaluated from simple resistance measurements. Expressions for the seven components of series resistance have been developed and evaluated for a two-bus cell fabricated at Solar Power Industries and having I_{sc} of 7.18 A, V_{oc} of 0.624 V, FF of 0.754, and η of 15.0% under standard one-sun conditions.

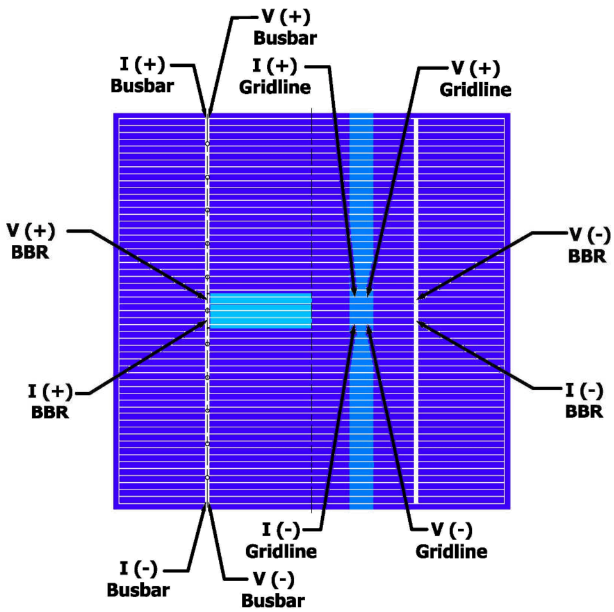

Fig. 1. Front grid pattern showing placement of probes in a four-point measurement for determining series resistance components associated with gridlines (BBR), busbar (Busbar), contact resistance and emitter sheet resistance (Gridline).

Front Busbar

The resistance of the busbar (R_{bus}) is measured by the four-point method, with current probes and associated voltage probes at opposite ends of the busbar as shown in Fig. 1. When applying the expression from [1], it must be noted that the measured busbar on the full cell has twice the width of the busbar of the elementary section. Hence, with busbar length (l) of 15 cm:

$$\rho_f/(tw') = 2^*R_{bus}/l. \quad (1)$$

This means:

$$r_s(\text{busbar}) = (1/3)^*an^2b^{2*}\rho_f/(tw') = (1/3)^*an^2b^{2*}(2^*R_{bus}/l). \quad (2)$$

Recall that a is 3.75 cm, n is 5, b is 0.13 cm, and l is 15 cm. With R_{bus} measured at 0.135 Ω, r_s(busbar) is calculated to be 0.010 Ω-cm^2 from (2).

Front Gridlines

The expression in [1] for series resistance associated with gridlines is:

$$r_s(\text{gridline}) = (2/3)a^2b\rho_f/(tw) \quad (3)$$

The line resistivity (ρ_f), width (w) and thickness (t) are not necessarily known and may not be uniform throughout the cell. However, the combination required [ρ_f/(tw)] in (3) can be related to the busbar-to-busbar resistance (BBR) measured as indicated in Fig. 1. Since the two busbars are separated by a length of 2a, and since BBR involves the parallel resistance of all gridlines connecting the busbars (n_{gl}), BBR can be expressed as:

$$BBR = [\rho_f/(tw)]^*(2a/n_{gl}). \quad (4)$$

Thus, from (4):

$$\rho_f/(tw) = (n_{gl}/2a)^*BBR. \quad (5)$$

Since the BBR measurement inherently averages all n_{gl} gridlines between the two busbars, it provides an accurate and convenient value needed to determine the gridline component of series resistance. The full expression for this component then becomes:

$$r_s(\text{gridline}) = (2/3)a^2b\rho_f/(tw) = (1/3)^*(abn_{gl})^*BBR. \quad (6)$$

For the 15 cm square cell under study, a is 3.75 cm, b is 0.13 cm, and n_{gl} is 57. Measured BBR of 0.0819 Ω thus gives r_s(gridline) of 0.759 Ω-cm^2.

Contact Resistance

Contact resistance is determined by cutting a slice from the cell parallel to the busbars and nominally 1 cm wide, as indicated by the lightly-shaded strip on the right in Fig. 1. This slice is typically taken between the two busbars, and must include only gridline segments (no busbar) in a “ladder” type of pattern. Cutting can be done by diamond scribe/break or by laser scribe/break. One set of probes, e.g., I(-)Gridline and V(-)Gridline of Fig. 1, is kept at the reference gridline, while the second set of probes, e.g., I(+)Gridline and V(+)Gridline, is placed first on a gridline one removed from the reference gridline, then on a gridline two removed from the reference gridline, for a total of about five gridlines. A current corresponding to current at one sun (≈ 10 mA) is injected via the current probes. For each gridline, the resistance (R = [V(+) – V(-)]/I) is determined. A plot of resistance versus gridline number gives a straight line. Measured data for the cell under study are plotted in Fig. 2.

Sheet resistance of the emitter layer is determined from the slope of the line. The number of squares between adjacent gridlines in the sample strip is given by line separation (2b) divided by strip width (w_{strip}). Thus:

$$R_{sheet} = \text{slope}/(2b/w_{strip}). \quad (7)$$

The slope in Fig. 2 is 8.73 Ω, 2b is 0.26 cm, and w_{strip} is 1.02 cm. Hence, from (7), R_{sheet} is 34.2 Ω/□.

Contact resistance associated with the interface between the gridline and the emitter layer is determined from the intercept on the Resistance axis. This intercept is effectively the resistance associated with two gridlines in the ladder. For screen-printed contacts on diffused layers with relatively high sheet resistance, the current transfer length (characteristic distance over which current transfers from the diffused layer to the gridline) is typically greater than half the width of the gridline. Hence, the effective area of the contact is the true geometric area, or the product of gridline width (w) by strip width (w_{strip}). Thus:

$$\rho_{contact} = (\text{intercept}/2)*(w w_{strip}). \quad (8)$$

For the sample under study, w is 0.0137 cm and w_{strip} is 1.02 cm. From Fig. 2, the intercept is –0.527 Ω, so $\rho_{contact}$ is calculated from (8) to be –0.00368 Ω-cm^2. This value is negative, and so unphysical, but small. It is interpreted as being zero within the sensitivity of the measurement, estimated to be ±0.005 Ω-cm^2.

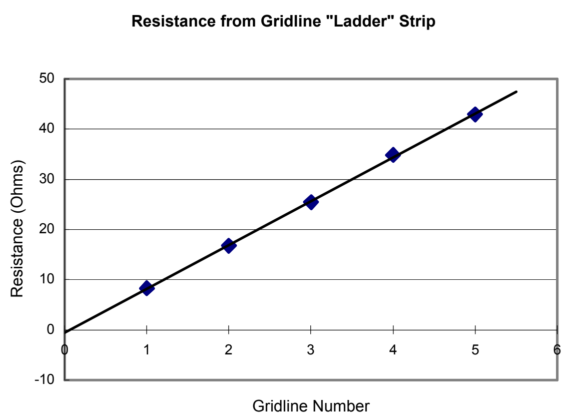

Fig. 2. Plot for extracting sheet resistance of the emitter layer (slope) and gridline-to-diffused-layer contact resistance (intercept) from a strip cut from the cell.

The contribution to series resistance associated with contact resistance is, in general, given by:

$$r_s(\text{contact}) = \rho_{contact}/(\text{fractional area covered}). \quad (9)$$

The fractional area covered is w/(2b). Combining this expression with (8) and (9) yields:

$$r_s(\text{contact}) = \text{intercept}*b*w_{strip}. \quad (10)$$

From (10) it can be seen that the contribution to series resistance from the contact resistance is independent of the width of the gridline. A sense of the magnitude of this contribution for the cell under study can be obtained by taking the absolute value of the intercept (0.527 Ω) along with 0.13 cm for b and 1.02 cm for w_{strip}. From (10), r_s(contact) is then 0.070 Ω-cm^2.

Emitter Sheet

This contribution depends on the spacing between gridlines (2b) and on the sheet resistance (R_{sheet}).

$$r_s(\text{emitter sheet}) = (1/3)*b^2*R_{sheet}. \quad (11)$$

With values of 0.13 cm for b and 34.2 Ω/□ for R_{sheet}, the value of r_s(emitter sheet) is 0.193 Ω-cm^2.

Substrate

This contribution depends on the bulk resistivity (ρ) of the wafer used and its thickness (t_w).

$$r_s(\text{substrate}) = \rho*t_w. \quad (12)$$

With a resistivity of 1 Ω-cm and a thickness of 0.027 cm, r_s(substrate) is 0.027 Ω-cm^2.

Back Metal

For cells connected in series in a module, current must travel through the back sheet of metal to get to the back busbar. This involves a series resistance similar to that of the front emitter sheet.

$$r_s(\text{back metal}) = (1/3)*a^2*R_{sheet}(\text{metal}). \quad (13)$$

With values of 3.75 cm for a and 0.00928 Ω/□ for R_{sheet}(metal), then r_s(back metal) is 0.044 Ω-cm^2.

Back Busbar

Considerations are the same as for the front busbar, but with dimensions and resistance of the back busbar taken into consideration. For the cell under consideration, the back bus bar is 2.5 times as wide as the front bus bar. Therefore, r_s(back busbar) is estimated to be smaller than that of the front busbar by that factor, or 0.004 Ω-cm^2.

Comparison of Components

Values are summarized in Table 1. Note that the front grid dominates the components at 73% of the total.

Table 1. Summary of series resistance components for 150 mm multicrystalline cell.

Component	Key Measurement	Measured Value	R_s (Ω-cm^2)
Front Busbar	Resistance Length of Busbar	0.135 Ω	0.010
Front Grid	Resistance Busbar-to-Busbar	0.0819 Ω	0.759
Contact Interface	Resistance vs. Bar Intercept	-0.527 Ω	0.000
Emitter Sheet	Resistance vs. Bar Slope	8.73 Ω/bar	0.193
Substrate	Resistivity/Thickness of Wafer	1 Ω-cm 0.027 cm	0.027
Back Metal	Sheet Resistance Back Metal	0.00928 Ω/□	0.044
Back Busbar	Resistance Length of Busbar	-	0.004 (est.)
TOTAL			1.037

Relation to Fill Factor

The reduction in fill factor (FF) corresponding to the total series resistance is given by [2]:

$$\Delta FF = -(J_{sc}/V_{oc})*R_s(\text{total})*FF_{ideal}. \qquad (14)$$

FF_{ideal} was measured using the Suns-V_{oc} technique to be 0.824. The cell under study has J_{sc} of 31.9 mA/cm^2 and a V_{oc} of 0.624 V. With a measured R_s(total) of 1.037 Ω-cm^2, ΔFF is calculated from (14) to be –0.044.

It is worth noting that R_s(total) can be reduced significantly by adding a third bus bar. With three bus bars, the value of a decreases from 3.75 cm to 2.50 cm. According to (3), r_s(gridline) scales as a^2, so r_s(gridline) is calculated to drop from 0.759 Ω-cm^2 for a two-bus cell to 0.337 Ω-cm^2 for a three-bus cell. This decrease would drop R_s(total) by 0.422 Ω-cm^2 from 1.037 Ω-cm^2 to 0.615 Ω-cm^2. Substituting this new value of R_s(total) into (14) yields a ΔFF of just -0.026. This reduction in loss of FF by 0.018 corresponds to an increase in efficiency of 0.36% (absolute), from 15.0% to 15.4%. Such a calculated increase in FF is consistent with observations for three-bus cells. The addition of a third bus bar could be done with almost no increase in shadowing, as the bus bar width is typically reduced from 2.0 mm for two-bus cells (4.0 mm total) to 1.5 mm for three-bus cells (4.5 mm total).

PSEUDO CONTACT RESISTANCE

A technique has also been developed to allow a coarse mapping of a parameter related strongly to contact resistance. Four sharp probes in a probe station are arranged as a four-point probe (in-line, equal spacing of $\approx$ 3 mm). These probes are placed between two gridlines where they penetrate the SiN_x anti-reflective coating and contact the silicon surface. If contact resistance is high, the resistance measured by the probes is that of the emitter sheet, since current cannot transfer easily from the emitter sheet to the gridlines. If contact resistance is low, the resistance measured is much lower, since current transfers easily from the emitter sheet to the gridlines and is carried largely by the gridlines. Fig. 3 shows a 3×3 mapping of a 15 cm cell where the contact resistance was non-uniform and high because the emitter n^+ sheet resistance was high (45 – 61 Ω/sq). Fig. 4 shows a similar mapping where the contact resistance was low because of lower n^+ sheet resistance (32 – 39 Ω/sq). This method is non-destructive (no cutting of the cell) for mapping pseudo contact resistance on a finished cell and is more direct and easier to apply than the destructive "ladder method." However, additional analysis is required to enable a conversion from the measured resistance to a true contact resistance. A finite element analysis has been initiated.

CONCLUSIONS

Four-point resistance measurements and analyses of the seven components of series resistance in a two-bus 15 cm square multicrystalline solar cell fabricated at Solar Power Industries with an efficiency of 15.0% indicate a total series resistance of 1.04 Ω-cm^2. The top three components were front gridlines (0.76 Ω-cm^2), emitter sheet (0.19 Ω-cm^2), and back metal (0.04 Ω-cm^2). This ranking suggests an efficiency gain of 0.36% (absolute) can be made by adding a third bus bar in order to shorten the length of the gridlines, thereby increasing FF by 0.018. It was found possible to make a coarse mapping of pseudo contact resistance in a non-destructive way on a finished cell using a probe station. With further development, this method may supplant the destructive ladder method for assessing contact resistance.

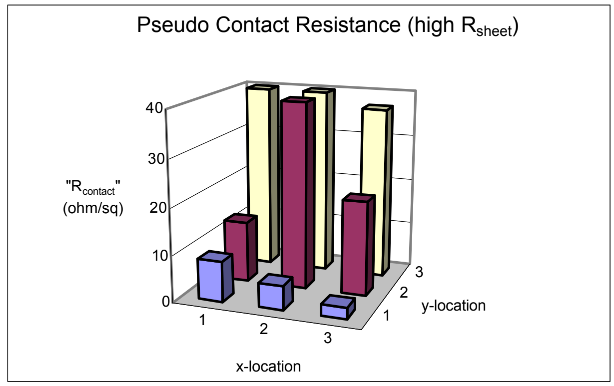

Fig. 3. High pseudo contact resistance map. Regions where "$R_{contact}$" is high (approximately equal to the sheet resistance of the emitter layer) indicate almost no transfer of current from the emitter layer to the gridlines.

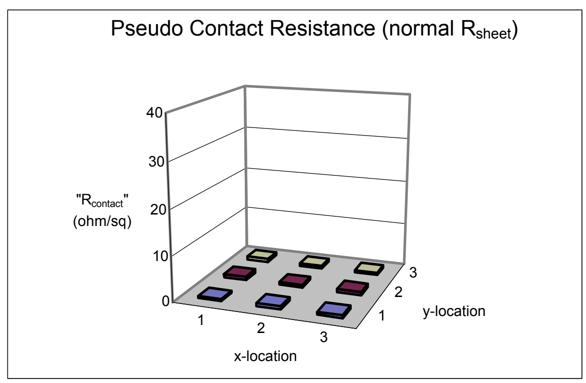

Fig. 4. Low pseudo contact resistance map indicating good transfer of current to the gridlines.

REFERENCES

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[2]. A. L. Fahrenbruch and R. H. Bube, *Fundamentals of Solar Cells*, Academic Press, 1983. pp. 220 – 222.