Presented at the 44th IEEE Photovoltaic Specialist Conference, June 25 2017, Washington D.C.

Non-Destructive Contact Resistivity Measurements on Solar Cells Using the Circular Transmission Line Method

Geoffrey Gregory[1], Andrew M. Gabor[2], Andrew Anselmo[2], Rob Janoch[2], Zhihao Yang[3], Kristopher O. Davis[1]

[1] Florida Solar Energy Center, Orlando, FL, 32826, USA

[2] BrightSpot Automation, Westford, MA, 01886, USA

[3] School of Materials Science and Energy Engineering, Foshan University, Guangdong, China, 528000

Abstract — **Several methods have been determined for measuring the contact resistivity of solar cell devices, but these methods are all either destructive in nature or require the fabrication of special metal contacts. In this paper, we present a non-destructive method for measuring the contact resistivity of commercial grade solar cells using the circular transmission line method. We first determine an optimal method for probing the total resistance of these structures on a solar cell and investigate the importance of measuring the exact dimensions of each contact. Then, by comparing the results of the measurement to traditional TLM results, we select a proper geometry for the circular patterns so that they can be hidden within the busbars of finished cells and not affect cell efficiency or aesthetic. Good correlation is demonstrated between automated circular TLM measurements performed on a new tool, the *ContactSpot-PRO*, and traditional TLM measurements performed manually. The implementation of this high-speed tool can allow contact resistance to be measured on every R&D or production cell with only a minor change in front silver paste screen artwork.**

I. INTRODUCTION

One critical component of series resistance in solar cell devices is the contact resistance R_C (ohms) or contact resistivity ρ_c (ohms-cm^2) between the metallization and the semiconductor. In order to optimize the performance of these devices it is important to accurately measure ρ_c after metallization. While customized test structures can be made for all of these measurements, other tests can also be performed on actual commercial-grade solar cells in a variety of ways, some being destructive in manner while others allow the cell to remain intact. A popular method of contact resistance measurement uses the Corescan tool from Sunlab [1]. This tool is most appropriate for spot checks as it has low throughput and is destructive since it uses a probe to scratch across the surface. A method for measuring ρ_c during production on a large set of cells is desirable as it would allow for the optimization and the monitoring of front metallization processes.

The transmission line method (TLM) [2, 3], is another common way of measuring ρ_c as well as the sheet resistance R_{sh} (ohms/sq) of the underlying doped Si layer and the transfer length L_T on commercial grade solar cells [4, 5]. When applying this technique to cells, the devices are cut into strips parallel to their busbars so that current flow can be isolated between incrementally spaced contact pairs and the resultant resistance can be measured. From there ρ_c is extrapolated from a plot of total resistance R_T versus contact spacing d. This method is often chosen over others because of its accuracy, but its destructive nature prohibits the use of the solar cell in its intended commercial application.

A variation of the TLM, known as the circular transmission line method (cTLM) [6], has also been used to measure ρ_c and R_{sh} non-destructively on semiconductor devices. Fig. 1 shows the general form of a cTLM structure with conducting inner regions of varying radius L, non-conducting regions with fixed radius r, and a conducting outer region with a variable width w. The difference between dimension r and L is designated as the gap size d.

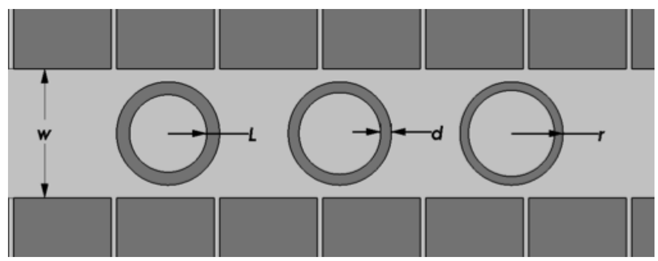

Fig. 1. cTLM structure with conducting inner region of radius L, non-conducting region of radius r and gap size d.

This method works in a similar manner to the TLM; R_T is measured between the outer conducting region and each of the inner dots while the incremental contact spacings are created using the variable dimension L. While this method is commonly used in many semiconductor applications, we have seen no published reference of its application to solar cell devices, although researchers from Suniva and the Rochester Institute of Technology have independently been exploring these approaches simultaneously with our work [7]. Due to the geometry of the cTLM structures there is no need for destructive edge isolation as in the TLM. Therefore, the method presents an opportunity for manufacturers and researchers to assess ρ_c on finished cells in a non-destructive manner.

In this paper, we detail a set of experiments in which cTLM structures were screen printed within the busbars of standard crystalline silicon (c-Si) solar cells and analyzed in an attempt to exploit the non-destructive nature of the method.

We detail the investigation of different front-side metallization designs driven by cTLM theory [8], as well as appropriate methods for probing R_T of each dot structure. The *ContactSpot-PRO*, an automated multiplexing tool with image recognition capabilities and a translation stage was built in conjunction with these experiments by BrightSpot Automation for in-line ρ_c characterization purposes with a takt time as short as 3 seconds. The importance of the accurate measurement of circular radii for parameter extraction is highlighted along with its incorporation into the tool. The results of the cTLM measurements are compared to the results of linear TLM measurements performed on the same set of cells to validate this novel solar cell characterization method.

II. EXPERIMENT

A. Metallization Design

The cTLM technique calculates the values of ρ_c and R_{sh} using different contact geometries, each with a slight variation in the dimensions L and r. The basis for the method, proposed by Schroder [8], defines R_T as a function of ln(1+d/L):

$$R_T = \frac{R_{SH}}{2\pi}\left[\frac{L_T}{L}\frac{I_0(L/L_T)}{I_1(L/L_T)} + \frac{L_T}{L+d}\frac{K_0(L/L_T)}{K_1(L/L_T)} + \ln\left(1+\frac{d}{L}\right)\right], \quad (1)$$

where I and K are the modified Bessel functions of the first kind and their subscripts denote their order. For situations where $L>>4L_T$, I_0/I_1 and K_0/K_1 approach unity and (1) can be simplified as:

$$R_T = \frac{R_{SH}}{2\pi}\left[\frac{L_T}{L} + \frac{L_T}{L+d} + \ln\left(1+\frac{d}{L}\right)\right]. \quad (2)$$

The cTLM structures designed for these experiments employed 6-circle arrays, where each circle within each array had unique values of r, L, and d. An R_T value was measured from each dot of the cTLM arrays and a Nelder-Mead solver was used to calculate the values of L_T and R_{sh} that corresponded to each data point measured.

To simplify the calculation of ρ_c and R_{sh}, the metallization screen designed for these experiments employed large circular contact radii that would meet the requirement $L>>4L_T$ so that (2) could be used as a solution method. This led to circular contact designs that were larger than many standard busbar widths (~1200 µm). Therefore, the busbars had to take on a unique shape near the cTLM contacts in order to compensate for the large radii. Fig. 2 shows one of these printed cTLM structures as well as a TLM structure used for validation of measured ρ_c.

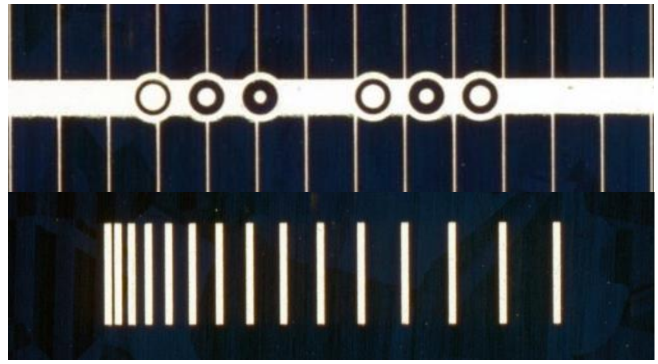

Fig. 2. cTLM contact on 1200 µm busbar after firing.

B. Metal Resistance

Different methods of probing the cTLM structures were analyzed to determine if additional line resistance was introduced when measuring R_T. The front side metallization was deposited and fired by Gonda Electronic Technology, Co. Ltd. using experimental Ag pastes at different peak firing temperatures. A Keithley 2400 Sourcemeter was used in combination with a micro-probing station to measure R_T; a current probe and voltage probe were then placed onto the inner dot of each circular contact while one voltage probe and one, two, or three current probes were placed on the outer region of the contact as shown in Fig. 3. This was done to assess the uniformity of current distribution along the busbar regions of the cTLM structures.

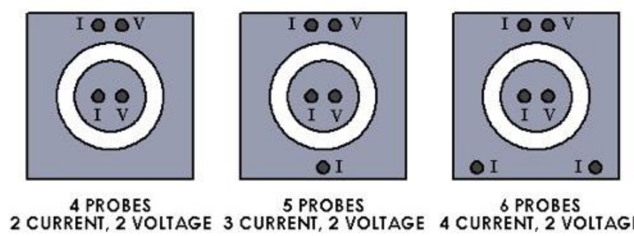

Fig. 3. Position of current and voltage probes on cTLM structures using four, five, and six probes.

The effect of metal resistance on the measurement technique was also assessed by varying the width w of the busbars. R_T was measured on several circular structures deposited within busbars of varying widths. This was done to assess whether using a targeted busbar width of 1200 µm would introduce unnecessary line resistance to the cTLM measurement.

C. Contact Dimension Measurement

During the printing and firing process of the front side contacts, the dimensions of the metallization are often different from the screen artwork design due to factors such as paste slumping, temperature variations, paste viscosity variations, and screen wear. These dimensions can vary spatially within a cell and from cell to cell. The cTLM contacts used in this study were designed with only small (~ 50 μm) incremental changes from one contact radius to the next, so slight changes in the cTLM dimensions had the potential to significantly impact the measurement results. Because of this, special attention was given to the actual contact dimensions after firing.

To study this, a confocal scanning microscope was used to record the actual dimensions of several cTLM contacts. An optical inspection camera with image processing software was integrated into the *ContactSpot-PRO* and then calibrated with the data taken from the confocal microscope. The focus, brightness, and ambient light intensity were all optimized on the optical unit until accurate dimension measurement was possible.

III. Results and Discussion

A. Metal Resistance

A plot of R_T versus ln(1+d/L) for the three studied probing schemes shows that the metal resistance has a significant effect on the total measured resistance when only four probes were used. Fig. 4 shows such a plot. By adding just one extra current probe to the outer ring of the cTLM structure, the measured values of R_T decreased by 35.8%. The remainder of experiments that were performed used five probes to measure the total resistance of each circular structure. Additionally, the *ContactSpot-PRO* probe head was designed with multiple current probes in order to minimize this added resistance.

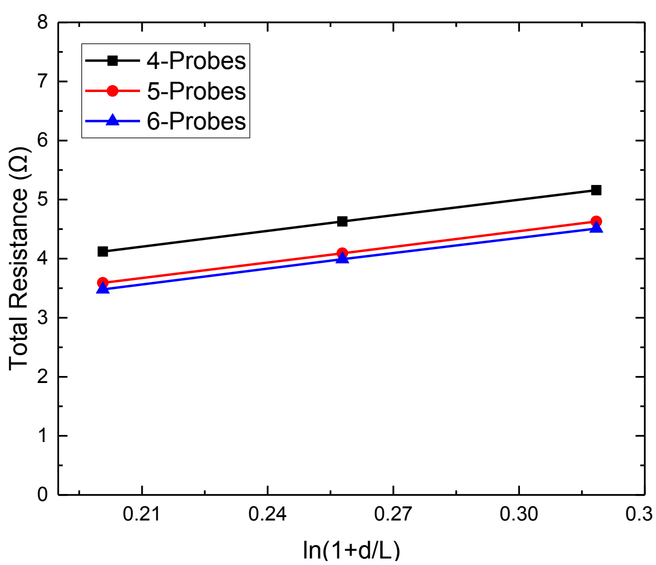

Fig. 4. Plot of R_T versus ln(1+d/L) for a sample fired at 855 ℃.

Fig. 5 shows a cTLM plot of two circular arrays, each with different busbar widths that were printed on the same cell. The first busbar had a width of 1200 μm and the second had a width of 4000 μm. Despite this, the resistance values gathered from each array were in good agreement with each other. A line of best fit was generated for the data taken from this cell with a coefficient of determination of 0.999. This test was repeated on several cells and the results were similar. Since the busbar width w showed little effect on the measured resistance values, 1200 μm busbars were used for the remainder of these experiments. In order to minimize shading losses and the front side contact fraction, the value of w should be small (≤ 1200 μm) in future applications.

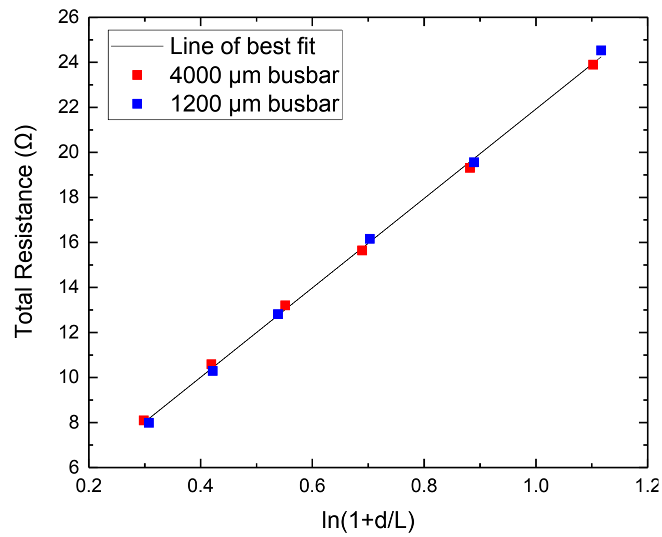

Fig. 5. cTLM plot of two circular arrays with different busbar widths from the same cell.

B. Results of Dimension Measurement Study

An error analysis was performed using the Nelder-Mead solver to investigate the magnitude of error that would result in the final value of ρ_c if the cTLM dimensions were systematically under-measured or over-measured. Typical values of ρ_c and R_{sh} (5 mΩ-cm^2 and 125 Ω/□) were implemented into the solver along with the designed cTLM dimensions, and theoretical R_T values were generated. The analysis showed that if the circular dimensions were systematically over-measured by just 1% then the error in ρ_c would be on the order of 11.4%. Similarly, the resultant error in ρ_c would be on the order of 10.8% if the circular dimensions were under-measured by the same magnitude.

The image recognition software and optical unit on the *ContactSpot-PRO* were calibrated with the measurements taken on the confocal microscope so that they would accurately measure the dimensions r and L on all of the cTLM structures used in this study. A statistical analysis was performed on the dimensions measured on 20 individual cTLM arrays by the tool and their deviation from their expected artwork values. The results of the analysis are shown in Table 1. Since the range of deviation was well above 1%, all the measured dimensions were used for the calculation of ρ_c and R_{sh} in order to minimize the error in the results.

TABLE 1
ANALYSIS OF CTLM DIMENSIONS

	Expected Dimension (µm)	Dimension Deviation (%)	Range of Deviation (%)
L_1	200	2.49%	4.99%
L_2	250	1.49%	3.29%
L_3	300	1.18%	3.55%
L_4	350	1.17%	2.19%
L_5	400	1.16%	3.08%
L_6	450	0.88%	1.96%
r	600	4.41%	4.11%

C. Results of cTLM Measurements

With the parasitic resistances of the measurement technique minimized and the image recognition software calibrated, ρ_c and R_{sh} were measured using both the linear TLM and the cTLM. This set of measurements was performed on p-type multi-crystalline silicon solar cells from Gonda with a range of sheet resistances and with different experimental front-side Ag pastes fired at 4 different peak temperatures over a range of 60C. The linear TLM was performed using the Keithley 2400 Sourcemeter after laser scribing the patterns from the cells. The cTLM was performed on the *ContactSpot-PRO*, shown in Fig. 6, using the calibrated optical inspection camera and the multiplexing probe head.

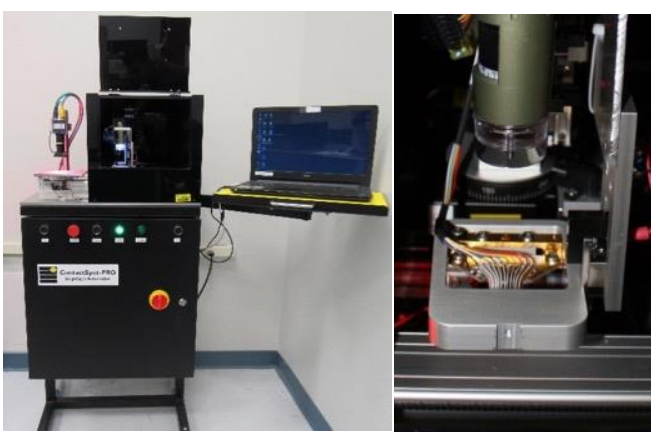

Fig. 6. The *ContactSpot-PRO* tool.

Fig. 7 shows that the values of R_{sh} that were calculated using (2) did not correlate well with the values of R_{sh} measured from the linear TLM structures. Since R_{sh} was over measured in this method, the values of ρ_c were consequently under measured. It is possible that the values of L may have not actually met the requirement for simplification, that $L >> 4L_T$.

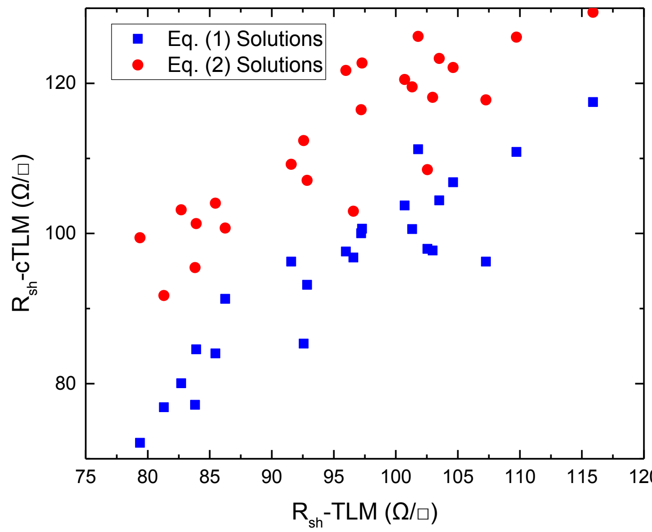

Fig. 7. Correlation plot of R_{sh} calculated using equations (1) and (2) from *ContactSpot-PRO* data versus R_{sh} calculated using the linear TLM.

The values of R_{sh} calculated using (1) did correlate well with the linear TLM data and with sufficient computational power, this calculation method will not affect takt times significantly. Fig. 8 shows promising correlation between ρ_c measured on the *ContactSpot-PRO* using the cTLM and the TLM data. The cTLM tended to undermeasure the values of ρ_c. This difference may be due to remaining inaccuracies in the measurement of circular dimensions. Implementation of a correction factor could also help improve the correlation.

Without the need to maximize the values of L to meet the requirements of (2), inner dot radii can be made to fit well within the bounds of narrow busbars. Thus, the contact fraction and shading losses of these types of cells can be even further minimized.

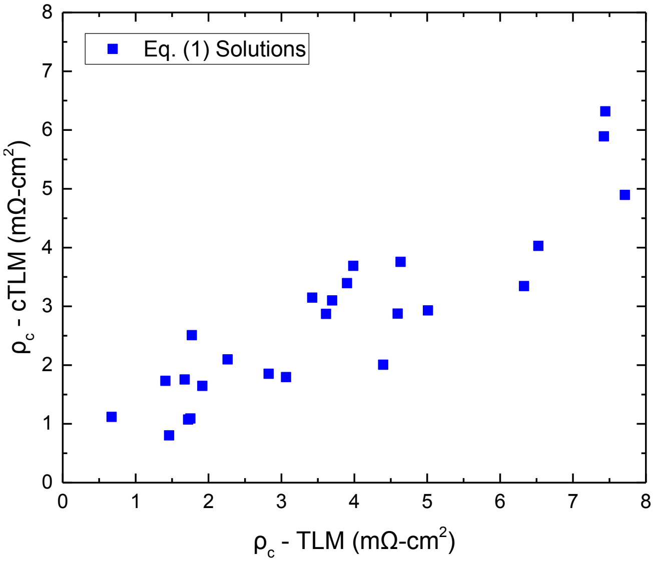

Fig. 8. Correlation plot of ρ_c calculated using equation (1) from *ContactSpot-PRO* data versus ρ_c calculated using the linear TLM.

IV. CONCLUSIONS

In these studies, we demonstrated a successful application of the circular TLM method on commercial grade solar cells. This nondestructive method allows measurement of cells for both research & development as well as production lines with only a minor change in screen artwork. The present semiautomatic tool allows the easy and fast testing of every R&D cell for improved experimentation. An in-line version of the *ContactSpot-PRO* tool located near the standard IV testing equipment could enable the testing of contact resistance and sheet resistance on every cell in a production line for improved factory quality control. Since the circular structures were hidden within the busbars, these structures will have essentially no impact on module aesthetics or power after soldering of the interconnect wires. It was determined that in order to account for the line resistance of these structures without compromising the functionality of the measurement, three current probes and two voltage probes should be used to measure the R_T of each dot. An optimal method for calculating the parameters of interest was identified by comparing its results to traditional TLM values. A specific cTLM geometry was then chosen to fit within the bounds of a 1200 µm busbar, with the potential to fit well within even narrower busbars in future photovoltaic applications. In cases where a floating busbar paste is used, the portion of the busbar that is printed with the cTLM patterns should be printed along with the fingers.

Future work will explore cTLM application to alternate metallization schemes such as 1) plating, 2) to rear side Al paste contacts to silicon through dielectric openings (PERC), 3) to metal on TCO application such as heterojunction cells, and 4) to thin-film applications for example by masking the metal deposition onto CdTe layers.

ACKNOWLEDGEMENTS

The authors would like to thank Gonda Electronic Technology, Co. Ltd. for providing the test cells and metallization for these experiments. This material is based upon work supported in part by the U. S Department of Energy's Office of Energy Efficiency and Renewable Energy, in the Solar Energy Technologies Program, under Award Number DE-EE0004947.

REFERENCES

1. Heide, A.S.H.v.d.S., A.; Wyers, G.P.; Sinke, W.C., *Mapping of contact resistance and locating shunts on solar cells using resistance anaysis by mapping of potential (RAMP) techniques.* 16th European Photovoltaic Solar Energy Conference and Exhibition 2000: p. 4.
2. Murrmann, H. and D. Widmann, *Current crowding on metal contacts to planar devices.* IEEE Transactions on Electron Devices, 1969. **16**(12): p. 1022.
3. Berger, H.H., *Models for contacts to planar devices.* Solid-State Electronics, 1972. **15**: p. 145-158.
4. Andrew M. Gabor, G.G., Adam M. Payne, Rob Janoch, Andrew Anselmo, Vijay Yelundur, Kristopher O. Davis, *Dependence of Solar Cell Contact Resistivity Measurements on Sample Preparation Methods.* IEEE Photovoltaic SpecialistsConference,, 2016. **43**.
5. Guo, S., et al., *Detailed investigation of TLM contact resistance measurements on crystalline silicon solar cells.* Solar Energy, 2017. **151**: p. 163-172.
6. Reeves, G.K., *Specific contact resistance using a circular transmission line model.* Solid-State Electronics, 1980. **23**: p. 487-490.
7. *Conversations with Adam Payne and Satosh Kurinec, 2016.*
8. Schroder, D.K., *Semiconductor material and device characterization.* 1990, New York: Wiley.