Contact Resistance Measurement – Observations on Technique and Test Parameters

Rob Janoch[1], Andrew M. Gabor[1], Andrew Anselmo[1], Christopher E. Dubé[2]

[1]BrightSpot Automation LLC, Westford, MA 01886, USA

[2]Applied Materials, 35 Dory Rd. Gloucester MA 01930 USA

***Abstract* — During testing of a new contact resistance measurement system (ContactSpot), we observed several unexpected results. TLM theory predicts a linear dependence of the resistance measurements vs probe spacing, and from this data set the contact resistance can be extracted. However, we found a non-linearity at wider probe spacing as well as sensitivities to the magnitude of the current, the direction of current flow, the ambient light level, and the choice of using contact pitch or spacing distances in the algorithm. Little appears in the literature concerning these effects and sensitivities. We found acceptable conditions for performing the TLM method in the dark, but we found more consistent results for contact resistance and emitter sheet resistivity values when using a previously developed algorithm that does not depend upon calculating slope and intercept values.**

***Index Terms* — contact resistance, photovoltaics cells, process measurements**

I. Introduction

The contact resistance in photovoltaic solar cells is the electrical resistance of the interface between the metal contacts and the underlying semiconductor material. A significant portion of the cell efficiency gains seen in recent decades within the mainstream crystalline silicon PV industry has been due to improvements made in the formulation of silver pastes that can form contacts with low resistance to emitters with ever lower doping levels. As the emitter doping levels decrease, the contact resistance generally increases for a particular paste and firing recipe. For advanced cell architectures, such as nPERT, contact resistance is even more important for both B and P doped regions. While this parameter is critical in limiting future gains in cell efficiency, it is seldom measured directly due to the destructive nature of the test (cutting strips from a cell), and the lack of quick, accurate, and cost-effective tools to perform the measurement. Rather, many engineers tend look at the series resistance component of the cell fill factor to judge the contact resistance. When the contact resistance measurement is performed, it is usually done by manually placing pairs of probe tips on a series of fingers (gridlines) - a challenging task that becomes steadily more difficult as finger widths shrink. Manually recording each data point and analyzing the data adds to the laborious nature of the measurement. Our goal is to provide a fast, low-cost, user-friendly and accurate tool to aid in process development and factory optimization concerning this most critical cell parameter.

In this work we provide some background on contact resistance measurements, explore the practical challenges in performing the measurements, and describe our learning from building two iterations of a semi-automated test system which we have named the ContactSpot.

II. Contact Resistance Background

Different solar cell designs have interfaces for which the contact resistance is important. Some of these are shown in Table 1. In addition the degradation pathway for conductive adhesives and films involves a deterioration in contact resistance. For this work, we concentrate on the dominant fritted-Ag paste contacts.

TABLE 1. Cell interfaces where contact resistance is important

Metal	**Substrate surface**	**Formation route, notes**
Fritted Ag paste	Dielectric coated Si	Fire through dielectric; precipitate Ag crystallites at/near interface.
Plated Ni	Si	Low-temp fire to form Ni-silicide interface layer
Low-temp Ag paste	TCO	Low temp fire to contact directly
Al paste	Si	Interface after firing is between eutectic Si-Al alloy and Al doped BSF region in Si. Not of concern for full-area BSF cells, but possibly relevant to PERC cells with reduced interface area.

The contact resistance R_C has units of ohms. However, the resistance value for any particular sample depends on the area of the metal/substrate interface. For this reason, the term ρ_C, the specific contact resistance or the contact resistivity, with units of ohm-cm^2, is used since it is independent of the sample geometry.

Measuring the contact resistance is important since it can be used as a response for optimizing cell processing parameters within R&D experiments or even within the operation of a factory line. Also, the design of the cell grid involves a co-optimization of many resistive and shading power-loss components. Using accurate values for the contact resistance can aid in the effectiveness of such grid design efforts.

Several mapping methods exist which can extract series resistance components that may be correlated to contact resistance to varying degrees [1]. These instruments often provide valuable information on the cell performance and spatial variations. However, a variety of effects can distort the values calculated for contact resistance, and the instruments tend to be quite expensive which limits their penetration within the PV community.

The most common method of directly measuring contact resistance is the Transmission Line (or Transfer Length) Method (TLM). The TLM method [2-3] involves injecting current with one set of probes and measuring the voltage drop with a separate set of probes placed on fingers with different spacings, as is shown in Figure 1. For the common Si cell structure, the voltage drop or resistance between gridlines depends on the resistance between the contacts and the silicon, but also on the resistance in travelling through the heavily doped emitter region from one finger to another.

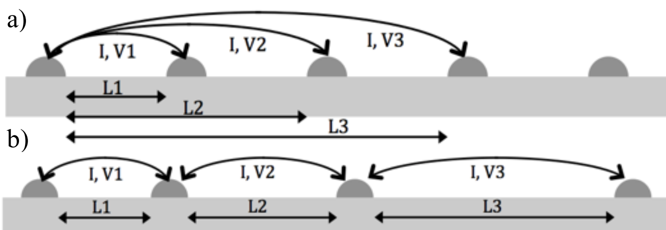

Fig. 1. Contact resistance probing approaches for a) equal-spaced, and b) variable-spaced contacts.

From a practical perspective, it is most convenient to apply the test to actual solar cells rather than special test structures. However, since busbars connect (short) the fingers together and since long fingers could introduce additional series resistance terms, generally narrow strips are scribed and snapped from full cells for this measurement. Thus, the destructive nature of the test does not allow its implementation within the factory on each cell.

Each strip has several gridlines spanning the narrow width of the strip. Critical parameters for each strip include the width *W* (same as the finger length), the emitter sheet resistivity ρ_{SH}, and the finger width *f*.

Once the charge carriers reach the edge of a finger, if the specific contact resistance is high and the sheet resistivity of the emitter beneath the finger is low, the carriers will tend to spread out and enter the finger uniformly over the interface with the silicon. Conversely, if ρ_C is low and ρ_{SH} is high, current crowding effects will take place and the carriers will tend to enter the finger just near its edge. The transfer length L_T describes the "usable width" of the finger, and is calculated to be [2-3]:

$$L_T = \sqrt{\rho_C / \rho_{SH}} \tag{1}$$

From this, the contact resistance (ohms) is:

$$R_C = \frac{\rho_C}{L_T W} = \frac{\rho_{SH} L_T}{W} \tag{2}$$

The measured resistance from the test R_M is then the sum of the resistance within the emitter between the two fingers with a spacing *L* and the contact resistance from current entering the effective width of each contact ($2R_C$):

$$R_M = \rho_{SH}\frac{L}{W} + 2\frac{\rho_C}{L_T W} = \rho_{SH}\frac{L}{W} + 2\frac{\rho_{SH} L_T}{W} = \frac{\rho_{SH}}{W}(L + 2L_T) \tag{3}$$

Thus, in a plot of R_M vs L, the y-intercept will give $2R_C$, the slope will give ρ_{SH}/W, and the magnitude of the x-intercept will give $2L_T$. Once one knows L_T, one can then calculate ρ_C. In the common case of the equal-spaced fingers, many researchers plot R_M vs. finger number (for example the Three Point Probe [4] method) which is equivalent to plotting vs the pitch (center to center distance) rather than the spacing between contacts. Differences between using the pitch and spacing are not discussed in the literature. Table 2 summarizes the various parameters.

TABLE 2. Parameters used in contact resistance tests

Parameter	Description	Typical value
I	Applied current in the strip	7 mA
L_x	Distance between 2 fingers	1-15 mm
V_x	Voltage measured between 2 fingers	30-150mV
R_M	Measured resistance	15-75 ohms
W	Strip width or finger length	1 cm
f	Finger width	65 microns
R_C	Contact resistance	0.2 ohms - for a 1-cm finger
ρ_C	Specific contact resistance or contact resistivity	0.003 ohm-cm^2
ρ_{SH}	Emitter sheet resistivity	85 ohms/square
L_T	Transfer length	?

While the above theory is straightforward, several groups have obtained questionable data from this approach [5-6] and real structures add complications. For example, real cells may have quite different ρ_{SH} values underneath or near the fingers in the case of selective emitters or in the case that the silver paste etches partway into the emitter, or in the case that a Ni-silicide layer consumes part of the emitter. Also, when using equal-spaced contacts on strips cut from cells, the current that passes by an unprobed, intermediate finger has the possibility not only to go underneath the finger, but also to enter the finger and move through the width of the finger and then back into the silicon near the opposite edge. This factor is not taken into account in the standard theory, and thus the variable-spaced approach may give more accurate results in some cases. Finally, real cells have spatial variations in sheet resistivity and contact resistance that add noise to the analysis. In general, since the transfer length adds an extra level of complication to the calculations, many experiments may be best performed by focusing on optimization of R_C rather than ρ_C. Most (all?) groups ignore the transfer length, and report an "effective" contact resistivity, $\rho_{C\text{-}eff}$, by using the full width of the finger instead of the transfer length:

$$\rho_{C-eff} = R_C W f \tag{4}$$

Several variations of the TLM method have been developed. One of particular interest, developed by Fraunhofer ISE, [1] uses just three fingers for each calculation of R_C. For finger number *x*, the contact resistance is:

$$R_{Cx} = \frac{R_{x,x-1} + R_{x,x+1} - R_{x-1,x+1}}{2} \tag{5}$$

where for example, $R_{x,x-1}$ is the measured resistance (voltage drop divided by the current) between finger number *x* and finger number *x-1*. Multiplying R_{Cx} by the finger area yields $\rho_{C\text{-}eff}$ from equation 4. The equivalent formula for sheet resistivity uses four fingers:

$$\rho_{SHx} = \frac{R_{x-1,x+1} + R_{x,x+2} - R_{x,x-1} - R_{x+1,x+2}}{2} \times \frac{W}{L1} \tag{6}$$

where L1 is the space between 2 adjacent fingers. Although the paper did not explore the application of the technique to calculating L_T and ρ_C, we know from the equation for a line and equation 3 that

$$y = slope * L + y_{intercept} = \frac{\rho_{SH}}{W} L + 2R_C \tag{7}$$

The x-intercept at y=0 yields $-2L_T$, so

$$L_T = \frac{R_C W}{\rho_{SH}} \tag{8}$$

and ρ_C can be calculated from equations 1 or 2.

The ISE group implemented their algorithm with a multiprobe head and an X-Y table to map ρ_C across long strips. By performing laser isolation scribes through the fingers and emitter (but not snapping the cell in strips), they demonstrated maps of ρ_C across an entire cell. One disadvantage of using such a multiprobe head is that generally, every time the finger spacing is changed, a new probe head is needed.

Finally, while most groups measure contact resistance by hand, which requires good dexterity, a sharp set of eyes, and good lighting, some papers allude to a possible complication from light induced effects [7].

II. EQUIPMENT DESIGN

The first iteration of our tester implemented a general purpose Keithley 2601 Source-Measurement unit to perform the current sourcing and voltage measurement functions. This unit is commonly used throughout the PV industry for a variety of measurement tasks. Its use allows for quick development time with the downside of significantly increased equipment cost. A printed circuit board contains the electronics for multiplexing between different probe pairs. A laptop computer controls the operation and collects data.

The tester is essentially a four-point ohmmeter with relays for switching the measurement between pairs of metallization fingers. Prior to the measurement, continuity is checked between the current and voltage probes on each finger. Each finger pair is measured twice, with the current direction reversed between the measurements. Although no more than 5 finger segments are generally needed to perform the measurement and achieve reasonable curve fitting, we designed the 1st system to accommodate up to 17 fingers for potentially higher accuracy and spatial mapping.

Initial measurements used a 10mm wide strip cut from the solar cell of interest. After evaluating a variety of different hand scribe and snap techniques, we settled on using two firm superimposed scribes with a tungsten carbide tip pen (e.g. – Ted Pella #829) on the front side, followed by snapping over a sharp support edge. Laser scribing or dicing with a dicing saw are superior methods, but are not available to all users.

Based on our learning from the first system and our increased confidence in the value of the measurement, we redesigned the system with the changes shown in Table 3.

TABLE 3. Design changes between the V1 and V2 iterations of the ContactSpot tester

Change	Motivation
Replaced the Keithley unit with a printed circuit board	Significantly lower system cost
Added a cover	Eliminate errors associated with sample exposure to light
Added a digital microscope and x/theta adjustment of the nest	Assist in test sample alignment
Reduced the total number of probe pins to 20 (10 current injection, 10 voltage measure)	Reduce system cost. Tests showed little value in using more than 5 fingers/test.
Staggered the pin layout with larger pin heads	Allowed one probe head to accommodate a wide range of finger spacings
Allocated 2 of the pins on the contact resistance probe head for line resistance measurements	Allow measurement of finger or busbar line resistance (ohms/cm) for increased system value
Designed an additional probe head for sheet resistivity measurements using standard 4pt probe method	With 20 pins, we can map 5 points across a variety of substrate sizes and layers (e.g. diffused layers, Al, TCO) for additional tool value
Automated software and data analysis with a choice of different algorithms	Increased ease of use and value

Both systems are shown in Figure 2.

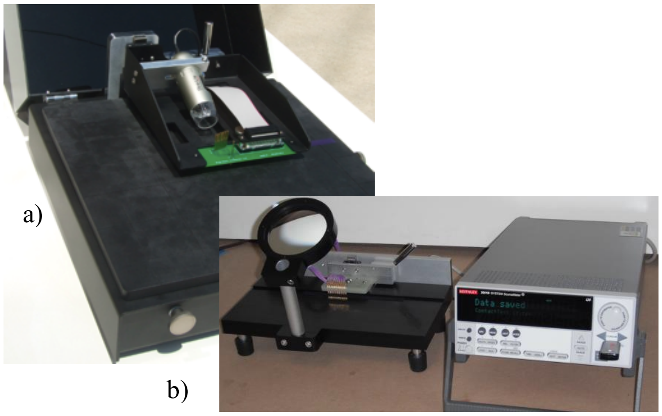

Fig. 2. a) V2 and b) V1 iterations of the ContactSpot.

Figure 3 demonstrates the advantage of our staggered probe array design. Particularly in R&D settings, finger pitch may frequently be changed, and allowing one probe head to accommodate a wide range of finger spacings is desirable. Some advanced cell designs use rear-side grids with finely spaced fingers that may fall outside the adjustability range of any particular probe-head. In such situations, every other finger can be probed as is shown in Figure 3d.

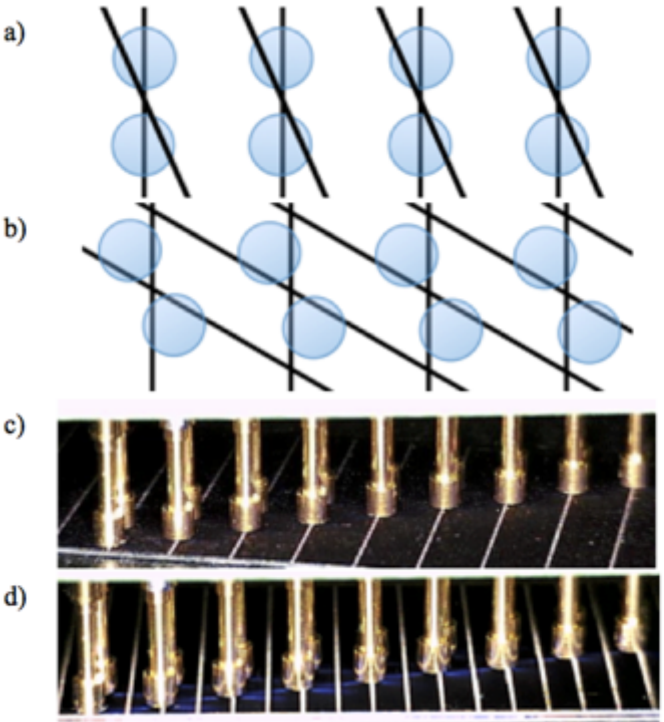

Fig. 3. Schematics of the top view of the a) 1st and b) 2nd iterations of the probe array design, where the staggered pin design allows for a much greater accommodation to different finger spacings by rotating the strips. ContactSpot screen alignment view of the staggered probe array for c) front and d) rear-side grids where every other finger is probed.

While we have concentrated our work on a probe head with constant spaced contacts, probe heads with variable spaced probes are also available are likely to give more accurate results by avoiding current paths through un-probed fingers. For other applications, any assignment of the 10 current and 10 voltage pins may be applied to customized probe heads and software written for measurements and data analysis.

III. DATA AND ANALYSIS

Common practice for contact resistance testing is to set the current to a value close to the operating level of the solar cell. In our case that would be about 7 mA (38 mA/cm^2 x 10 mm x 1.77 mm), and to use the measurements from ~6 fingers to establish a linear curve fit. Since most measurements are performed manually in a laboratory setting, the measurements are most commonly performed under ambient room light or focused work lights. Here we explored using a larger number of fingers for each measurements by the TLM method as well as the effect of varying the illumination intensity.

Fig. 4a shows a plot of typical data taken during our v1 tester characterization. Each point on the plot is a resistance measurement made between two fingers as a function of the pitch of the fingers. Two sets of data are shown: one taken at 2 mA current and another at 20 mA. The red points are positive current (flowing left to right as plotted) the black points are negative current. The dashed lines are linear fits to the closest two data points (1.8 mm and 3.5 mm finger spacing) of each data set. Fig. 4b shows an expanded view of the data in Fig. 4a, showing the y-intercepts of the two lines.

Generally, the slope of the plots decreases with increasing distance, and similar behavior has been documented by other groups [5]. This effect is pronounced with the positive 20 mA data points. In addition, the intercept (and hence the calculated contact resistance) is significantly higher for the 20 mA plot. Had a linear fit been made to all 16 of the positive 20 mA data points, the intercept would have been an order of magnitude higher than the intercepts in Fig. 4b. We saw similar effects of non-linearity and current polarity dependence when measurements were made in ambient room light or direct illumination with a work light.

We are in the process of developing an explanation for these effects. They may have the same underlying mechanism; perhaps an imposed or induced voltage effect. Note that the 20 mA current source produces 0.4 V in a measurement across 17 fingers in our samples. Common wisdom is to avoid voltages above ~0.2 V during contact resistance testing, but we were seeing effects well below 0.1 V imposed voltage. Instrument errors were ruled out by measuring a known resistor. In any case, we conclude that using large numbers of fingers to perform the TLM method is not desirable. This finding influenced our decision to reduce the number of probes in the v2 tester.

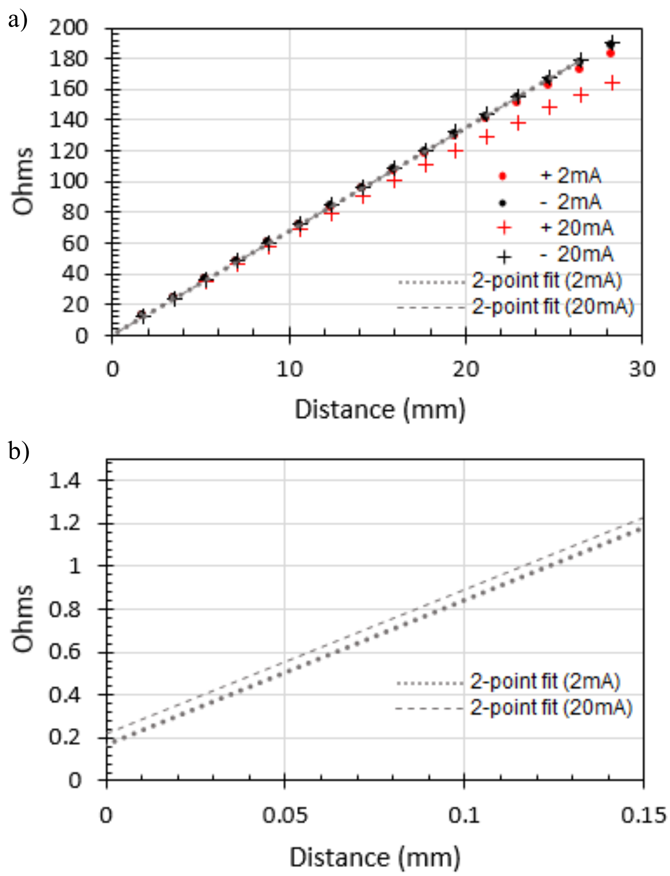

Figure 4 – (a) Resistance and distance between fingers measured. (b) Expanded scale.

In another test we compared three different algorithms: the TLM method using both 2 and 6 points for the fitting the line, and the ISE method. For the distance L in equation 3 and L1 in equation 6, we compared using the finger pitch vs finger spacing. We also compared two different levels of current. We used the x-intercept values to calculate L_T, and then used L_T to calculate ρ_C. We used the entire finger area to calculate $\rho_{C\text{-eff}}$. These results, summarized in Table 4, show significant difference between the methods, with the 6-point TLM method consistently yielding higher values of ρ_C and $\rho_{C\text{-eff}}$. The L_T values, in some cases, indicate a modest level of current crowding at the edges of the contacts.

TABLE 4. Comparison of testing methods

Spacing or Pitch	I (mA)	Method	$\rho_{c\text{-eff}}$ (mΩ-cm²)	ρ_{SH} (Ω/□)	L_T (µm)	ρ_c (mΩ-cm²)
Pitch	2	TLM 2pt	0.794	84.65	14.4	0.176
Pitch	2	TLM 6pt	1.814	83.77	33.3	0.930
Pitch	2	ISE	1.002	90.86	17.0	0.262
Pitch	20	TLM 2pt	1.267	83.72	23.3	0.454
Pitch	20	TLM 6pt	4.234	80.96	80.5	5.241
Pitch	20	ISE	1.486	89.84	25.5	0.582
Spacing	2	TLM 2pt	2.582	84.65	46.9	1.864
Spacing	2	TLM 6pt	3.584	83.77	65.8	3.629
Spacing	2	ISE	1.002	87.52	17.6	0.272
Spacing	20	TLM 2pt	3.036	83.72	55.8	2.605
Spacing	20	TLM 6pt	5.945	83.20	109.9	10.054
Spacing	20	ISE	1.486	86.54	26.4	0.604

In another test we examined the interaction of the test current and direction with the brightness of light hitting the sample during testing using the ISE algorithm and the v2 tester. Each data point in Figure 5 was found by mapping the contact resistance across a strip contacted by 9 pairs of probe tips. Since each calculation requires 3 fingers, this resulted in values assigned to 7 separate fingers, where each cluster of 3 fingers was tested 5 times With increasing amounts of sample illumination, we see higher values of ρ_C, lower values of ρ_{SH}, and higher variability and sensitivity to current direction. Variability was also reduced by higher current levels. We found in the dark case that the average of the coefficients of variation for the 7 separate finger tests increased from 1.0% to 1.6% to 3.2% as the current decreased from 20 to 5 to 2 mA.

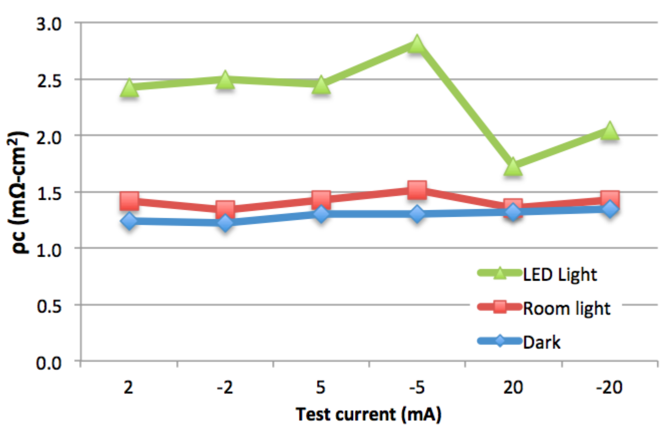

Fig. 5. Contact resistivity (ISE method) vs test current and sample illumination.

By using a strip with a large number of fingers, the measurement can be repeated by incrementing the leftmost finger in each test, and thus map the properties across the sample, as is shown in Figure 6. This particular strip showed a significant variation in effective contact resistivity. If desired, an entire cell could be mapped by such a method by cutting the cell into several strips. Future versions of the ContactSpot software may perform this task.

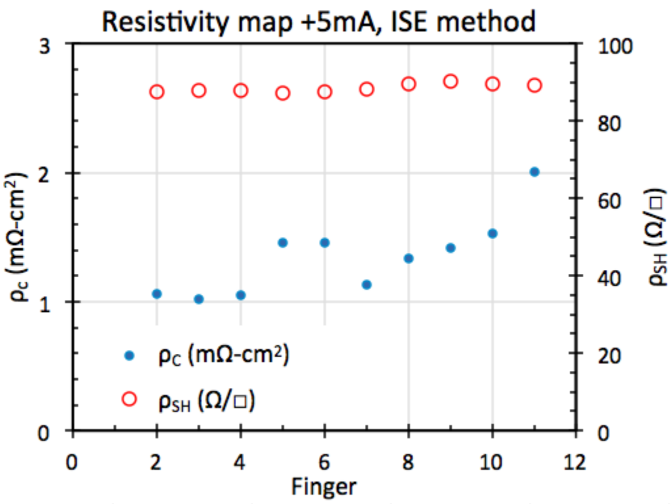

Fig. 6 – Spatial map of contact and sheet resistivity across several fingers on a strip

IV. CONCLUSIONS

The contact resistance test is best performed using either the classic TLM method with 5 or fewer fingers per measurements, or using the ISE method [1] with just 3 fingers per measurement. With the TLM method, significant differences in the values are seen depending on whether pitch or spacing values are used in the calculation. This sensitivity applies as well to transfer length calculations. While either method may be successfully used in experiments to optimize processes designs, or materials, for modeling purposes, it is more critical that accurate values are calculated. Further work is needed to determine the optimum algorithm and optimum current levels. The measurement should be performed in the dark using semi-automated equipment. We hope that this improved understanding of testing conditions/algorithms to increase the test accuracy and repeatability, together with the semi-automated equipment to greatly increase the speed and convenience of the test, will enable improved use of contact resistance measurements within the PV industry.

In future work we will collaborate with other groups to explore other contact resistance applications. For our part, we can design customized ContactSpot probe heads for different sample geometries and customized software for different data collection and analysis algorithms. It is interesting that while specific contact resistance measurements are widely reported in the literature, sheet resistivity and transfer length data from TLM measurements are almost completely absent. One topic of interest may include transfer length measurements as a function of cell processing conditions and finger width. The values we report here are the first that we are aware of in the modern PV literature and indicate some modest level of current crowding on the edges of the fingers. We also used the transfer length values to calculate an actual contact resistivity rather than an effective contact resistivity which assumes the entire contact area is utilized equally. If current crowding effects are indeed present for standard cells, then one benefit of the trend toward narrower fingers may be a more effective use of the full width of the fingers for current transfer from silicon to silver. Grid design optimization approaches so far ignore such an effect. Additionally, application of the technique to thin film PV may be of interest [8].

REFERENCES

[1] S. Kontermann et al, “Spatially resolved contact-resistance measurements on crystalline silicon solar cells,” *Phys. Status Solidi A* 206, No. 12 , pp. 866-2871, 2009.

[2] D. L. Meier and D. K. Schroder, “Contact Resistance: Its Measurement and Relative Importance to Power Loss in a Solar Cell,” *IEEE Trans. Electron Devices*, ED-31, pp. 647-653, 1984.

[3] D. K. Schroder and D. L. Meier, “Solar cell contact resistance - a review,” *IEEE Transactions on Electron Devices,* vol. 31, no. 5, pp. 637-647, 1984.

[4] P. N. Vinod, et. al., “A novel method for the determination of the front contact resistance in large area screen printed silicon solar cells,” *Semicond. Sci. Technol.* 15 pp. 286-90, 2000.

[5] D. L. Meier et al, “Determining components of series resistance from measurements on a finished cell,” *IEEE 4th World Conf. on Photovoltaic Energy*, 2006, p. 1315.

[6] M. Melczarsky et. al., "Contact resistance measurement techniques for Ag thick-film screen-printed contacts to solar cells," *34th IEEE Photovoltaic Specialist Conference*, 2009, p.960.

[7] F. Zeng et. al., “Specific contact resistance measurements on C-Si solar cells by novel TLM method,” *38th IEEE Photovoltaic Specialist Conference*, 2012, p.509.

[8] J. Klaer, R. Klenk, A Boden, A Neisser, C. Kaufmann, R. Scheer, and H.-W. Schock, "Damp Heat Stability of Chalcopyrite Mini-Modules: Evaluation of Specific Test Structures, " *31st IEEE Photovoltaic Specialist Conference*, 2005, p. 336.