Non-Destructive Contact Resistivity Measurements on Industrial Solar Cells

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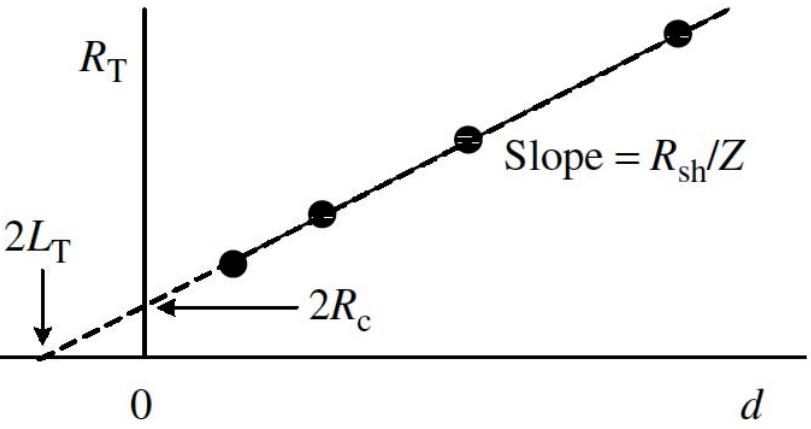
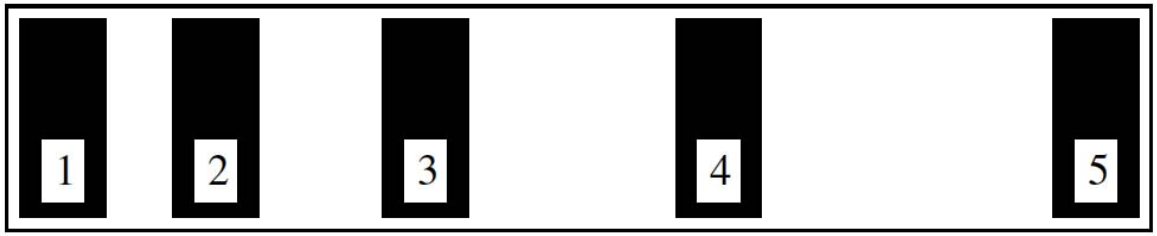
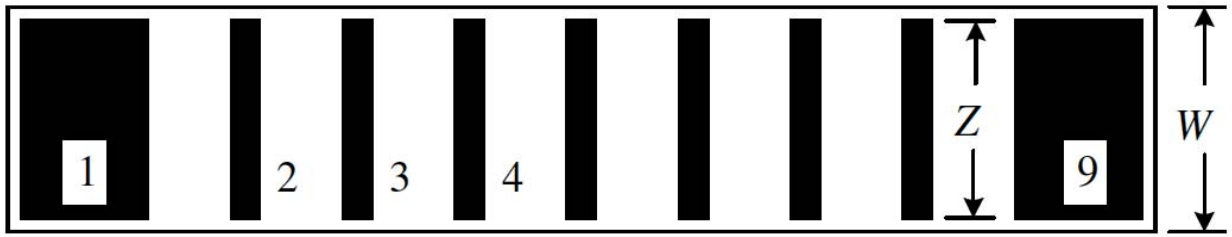
Contact Resistivity Structures



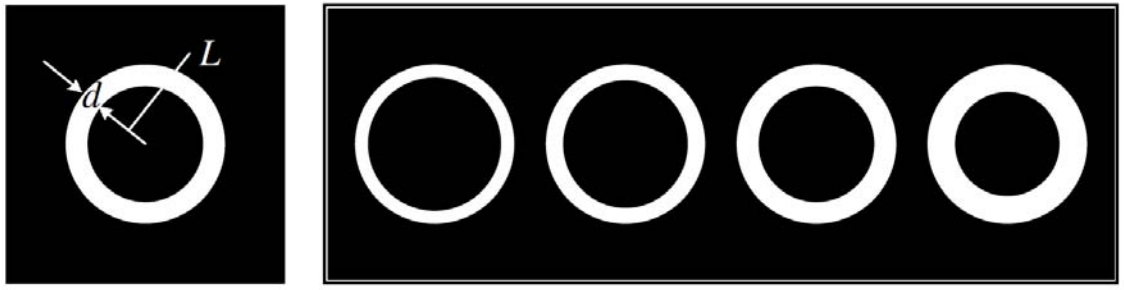
Linear variable spaced transfer length method (TLM)



Linear equivalently spaced TLM (i.e., ladder)



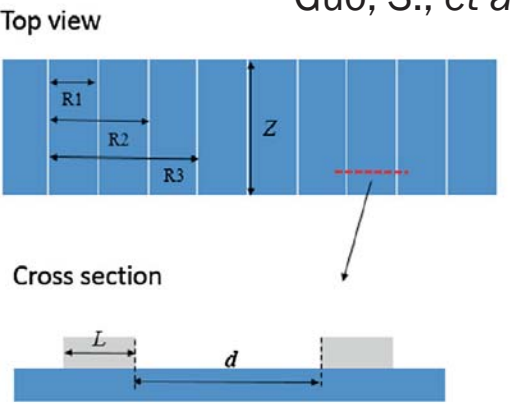
Circular TLM (cTLM)

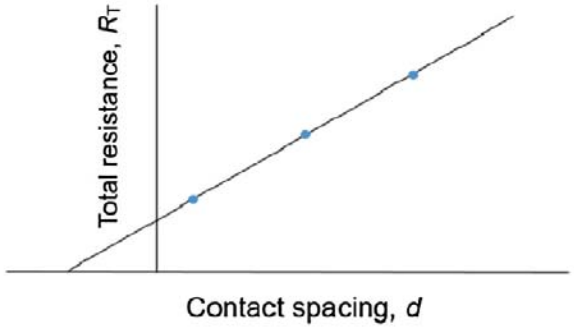


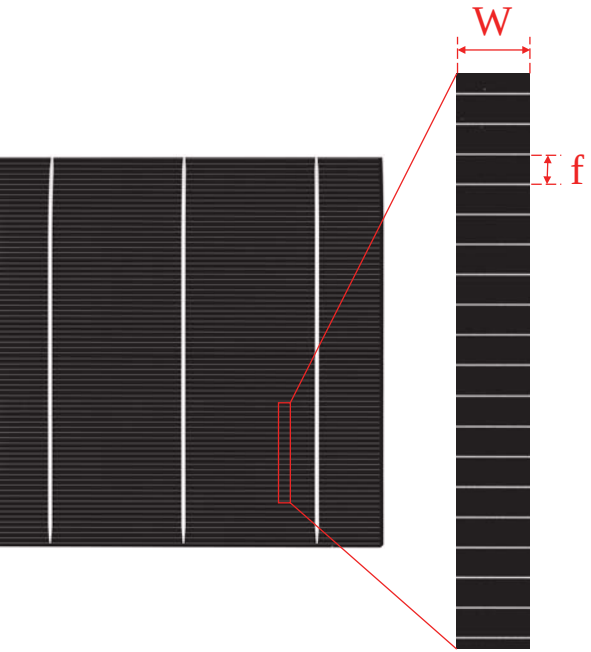
Schroder DK. *Semiconductor Material and Device Characterization* (1990).

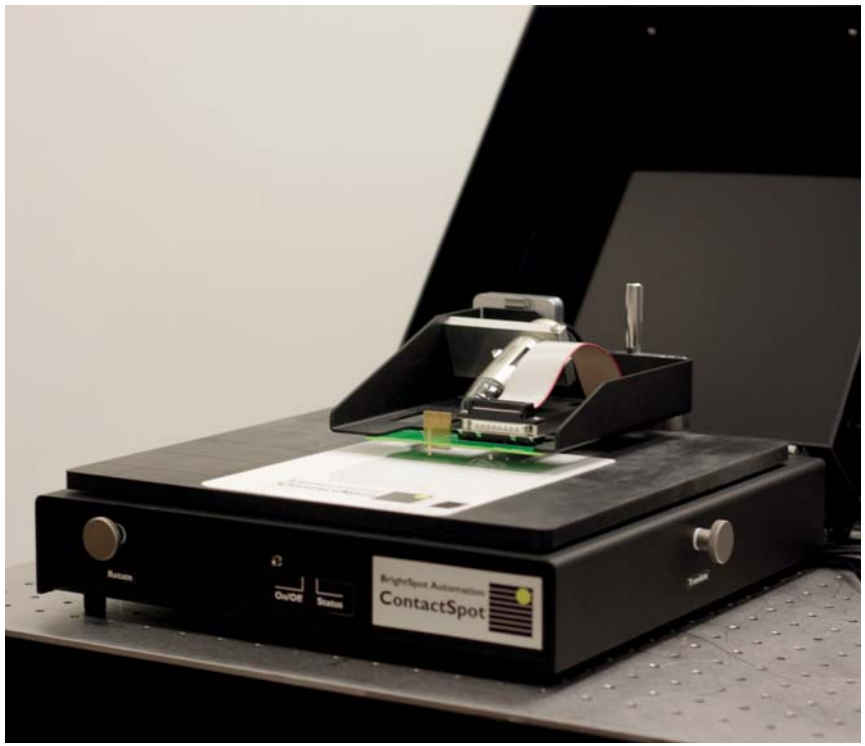
Linear TLM

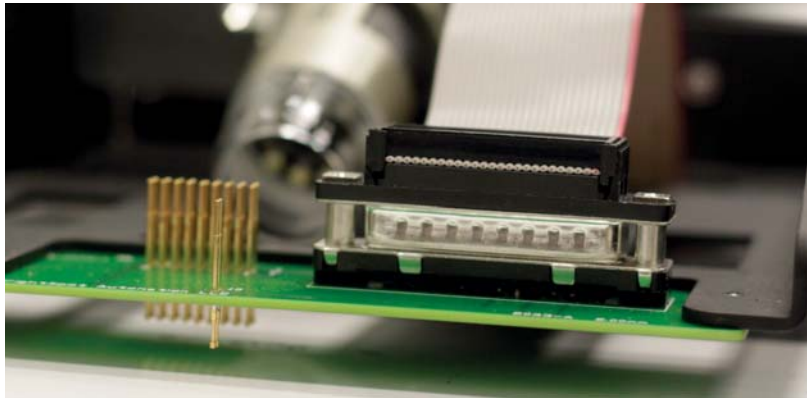
Guo, S., *et al.*, *Solar Energy*, 2017.





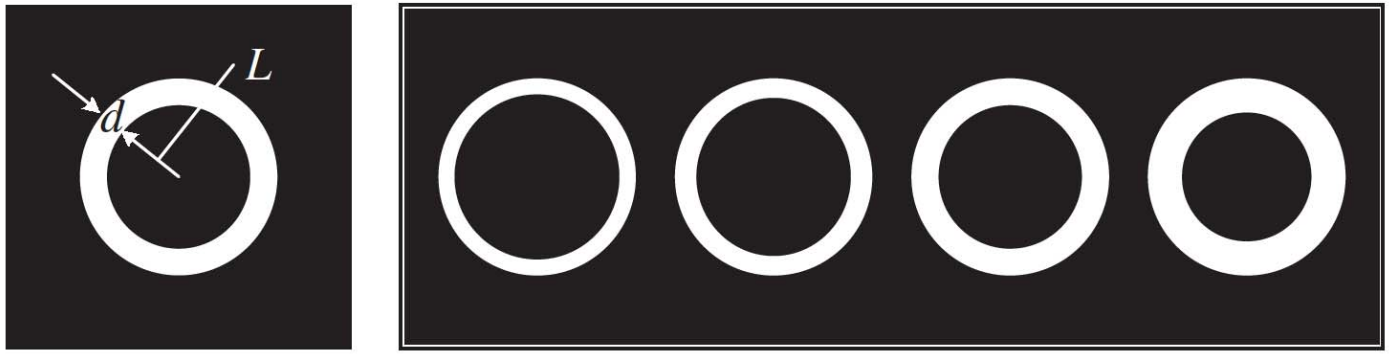






cTLM

- cTLM structures have a big advantage over linear TLM – it's non-destructive
- Because of current flow being restricted between the inner and outer rings, no physical isolation of the test structure is required

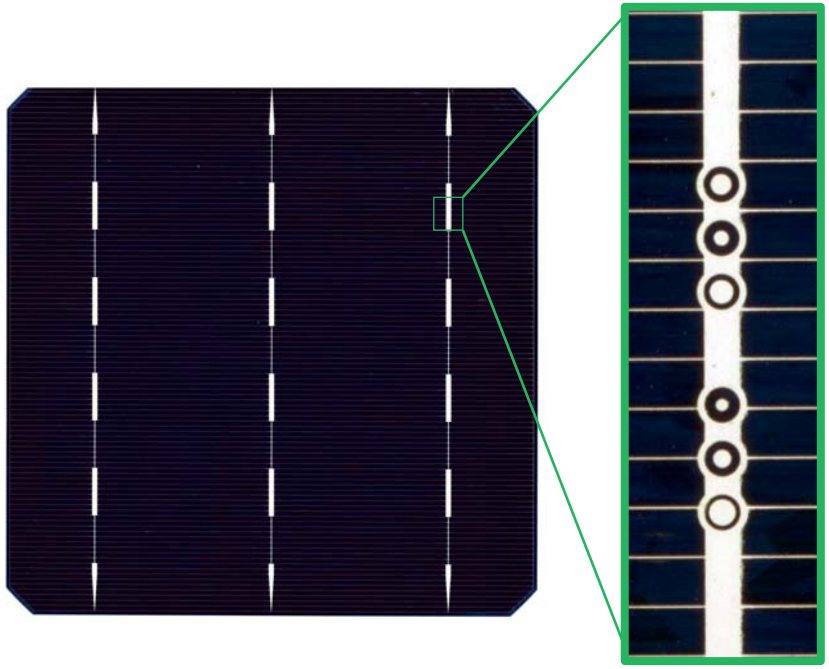


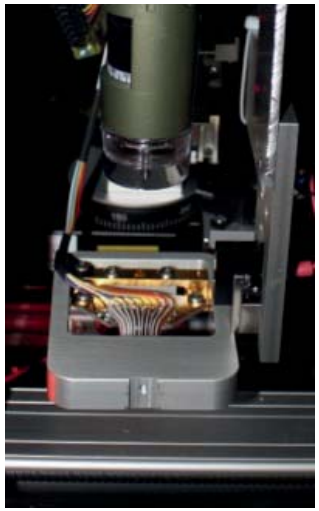
Schroder DK. *Semiconductor Material and Device Characterization* (1990).

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

Non-Destructive Contact Resistivity on Industrial Cells

- With BrightSpot Automation, we've co-developed a non-destructive using circular TLM's hidden in the busbars
- BrightSpot Automation now builds a semi-automated tool, the ContactSpot-PRO, to implement this measurement

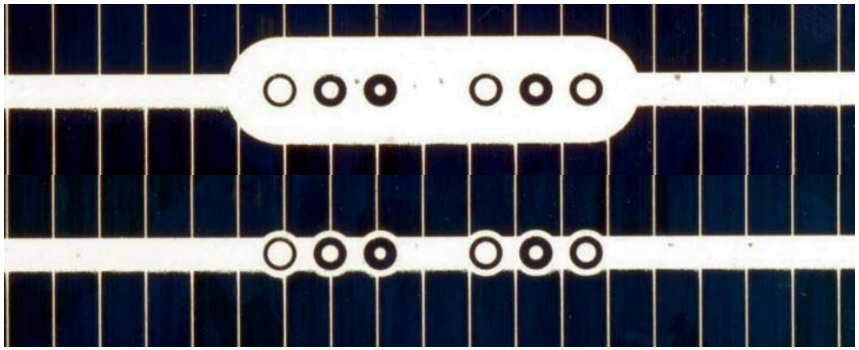


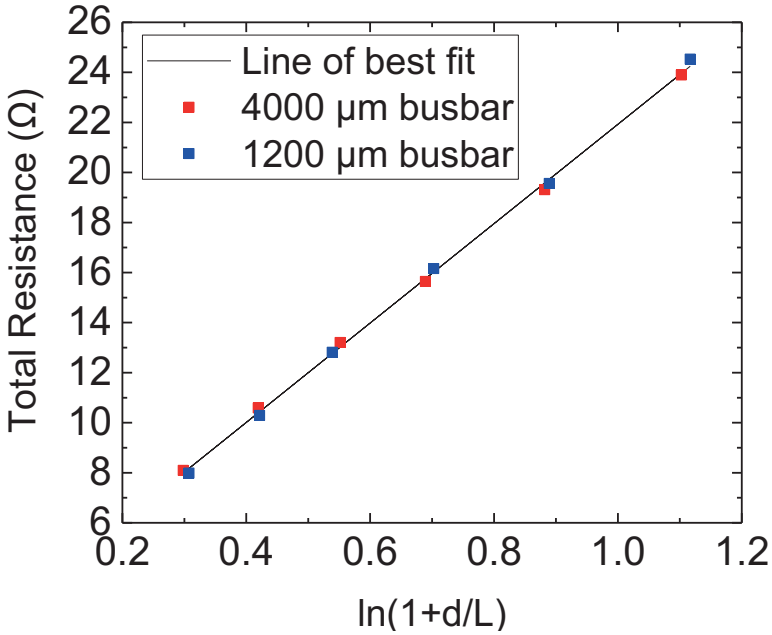


G. Gregory, *et al.*, *44th IEEE PVSC*, 2017.

cTLM Test Structure Designs

- Influence of the outer ring thickness on the total resistance (R_T) measured
- Initially curious about potential voltage drop around thinner outer rings
- Ultimately, thicker (top) and thinner (bottom) busbars yield same result, indicating voltage drop for thin outer rings is not an issue



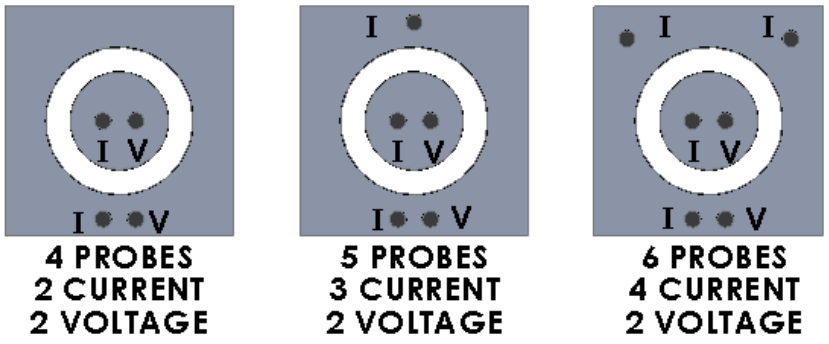


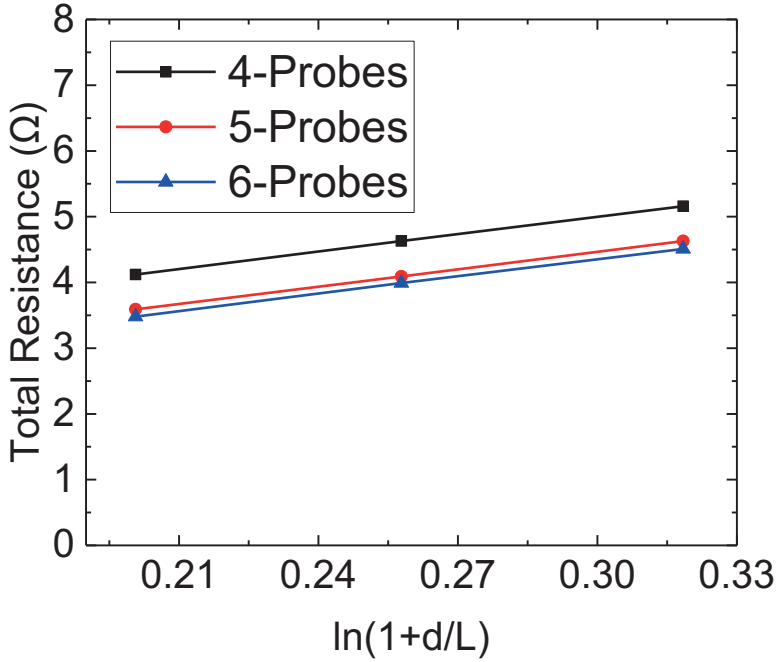
$$R_T = \frac{R_{sheet}}{2\pi}\left[\frac{L_T}{L}\frac{I_0(L/L_T)}{I_1(L/L_T)} + \frac{L_T}{L+d}\frac{K_0(L/L_T)}{K_1(L/L_T)} + \ln\left(1+\frac{d}{L}\right)\right]$$

G. Gregory, *et al.*, *44th IEEE PVSC*, 2017.

Contact Probing

- Special attention was given to the effect of metal resistance on the measurement results
- Adding a third current probe, reduced R_T significantly (≈35%)
- Adding a fourth current probe only slightly reduced R_T (≈2%)
- ContactSpot-PRO probe head designed with multiple current probes to minimize added metal resistance

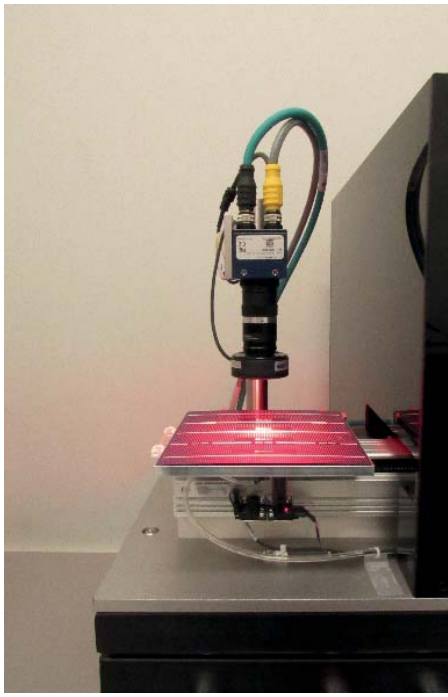




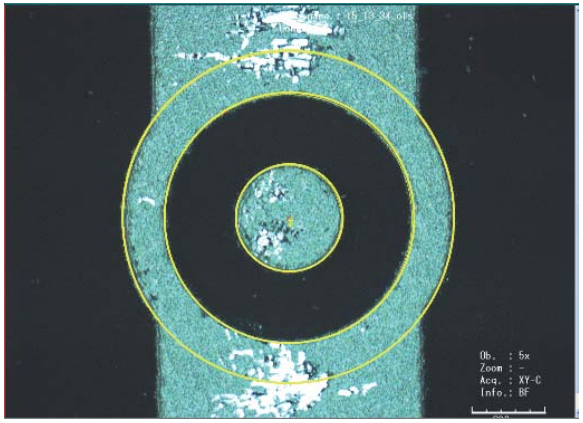
Dimension Measurements

- Measurement of actual cTLM dimensions required due to variation from wafer-to-wafer and structure-to-structure
- Small errors in the gap distance can yield large error in R_{sheet} and even larger error in ρ_c
- Camera and image processing software used in the ContactSpot-PRO allow for real time measurent of all test structures measured

ContactSpot-PRO Vision Sy



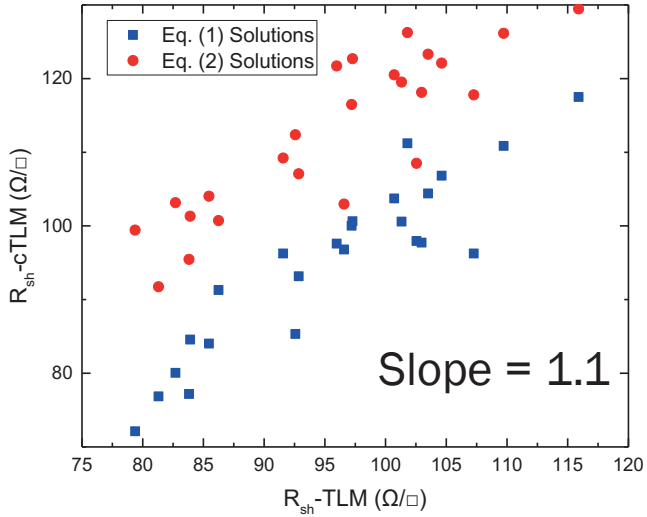
Optical Microscope

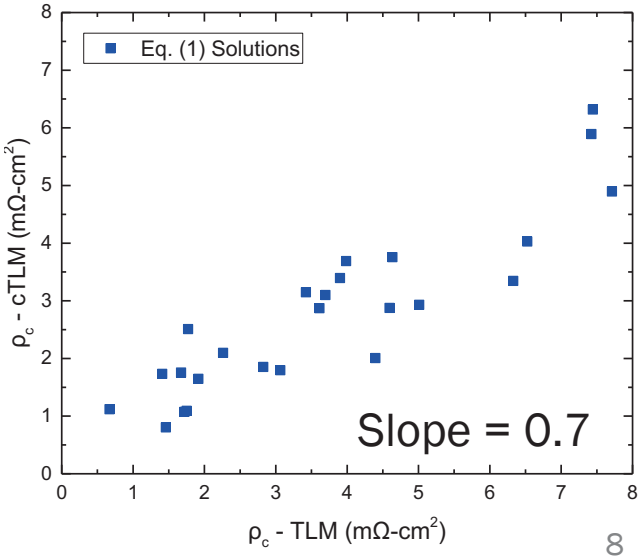


Example 1 Inner Dots Over-Estimated by 3%		Example 2 Inner Dots Under-Estimated by 3%	
Actual ρ_c (mΩ-cm^2)	5.00	Actual ρ_c (mΩ-cm^2)	5.00
Measured ρ_c (mΩ-cm^2)	6.78	Measured ρ_c (mΩ-cm^2)	7.72
% Error in ρ_c	35.6%	% Error in ρ_c	54.4%
Actual R_{sheet} (Ω/□)	125.0	Actual R_{sheet} (Ω/□)	125.0
Measured R_{sheet} (Ω/□)	121.3	Measured R_{sheet} (Ω/□)	116.5
% Error in R_{sheet}	-2.96%	% Error in R_{sheet}	-6.81%
R_T Error (RSS)	0.27%	R_T Error (RSS)	0.17%

Comparison: Linear TLM vs. cTLM

- R_{sheet} measured using the cTLM correlated very well with R_{sheet} measured using linear TLM
- ρ_c measured using the cTLM correlated well with ρ_c measured using linear TLM
  - ρ_c measurements sensitive to special variations
  - Magnitude of ρ_c values make variations apparent





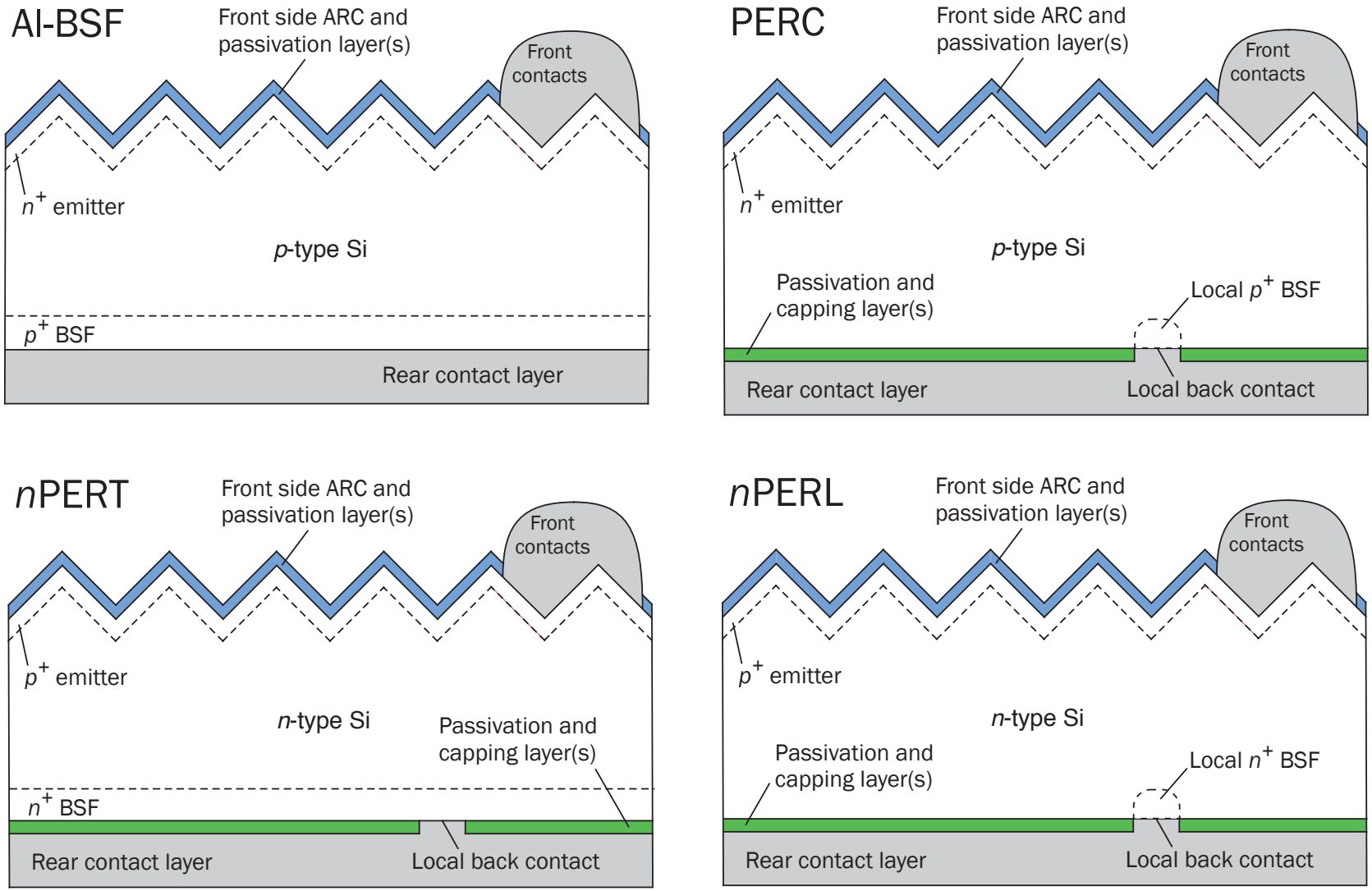
Eq. 1 $$R_T = \frac{R_{sheet}}{2\pi}\left[\frac{L_T}{L}\frac{I_0(L/L_T)}{I_1(L/L_T)} + \frac{L_T}{L+d}\frac{K_0(L/L_T)}{K_1(L/L_T)} + \ln\left(1+\frac{d}{L}\right)\right]$$

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

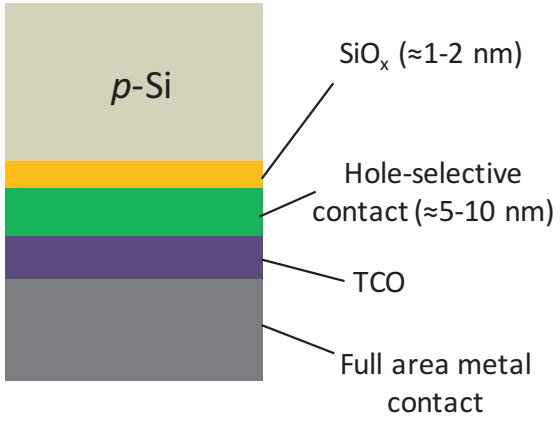
Current and Future Efforts

- More detailed uncertainty analysis
- Measuring large data sets with comparisons and correlations between cTLM parameters and *I-V* + Suns-V_{OC} parameters
- More research into how this data can be used in manufacturing for R&D efforts, quality control, and process control
- Perform measurements and investigate results for different contact materials, cell architectures, and contact interfaces

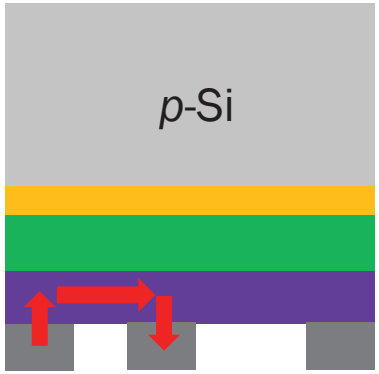
Different Cell Architectures



Different Cell Architectures



- Tunneling through SiO_x layer
- Interfacial contact resistivity between the SiO_x layer and hole-selective contact
- Series resistance due to the bulk of the hole-selective contact (if too thick or resistive)
- Interfacial contact resistivity between the hole-selective contact and TCO or metal
- Lateral series resistance of the TCO (bifacial only)
- Interfacial contact resistivity between the TCO and metal



- Lateral series resistance of the TCO
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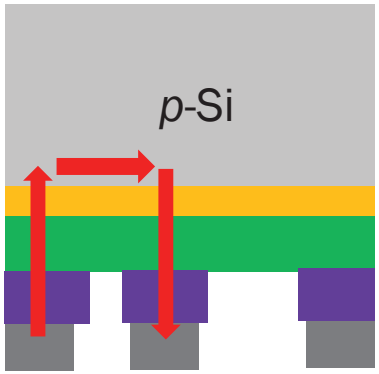

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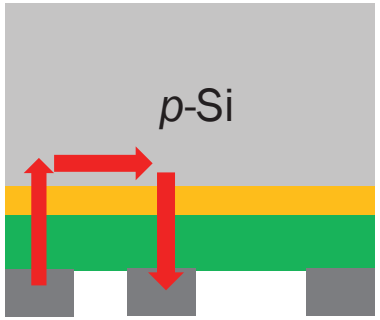

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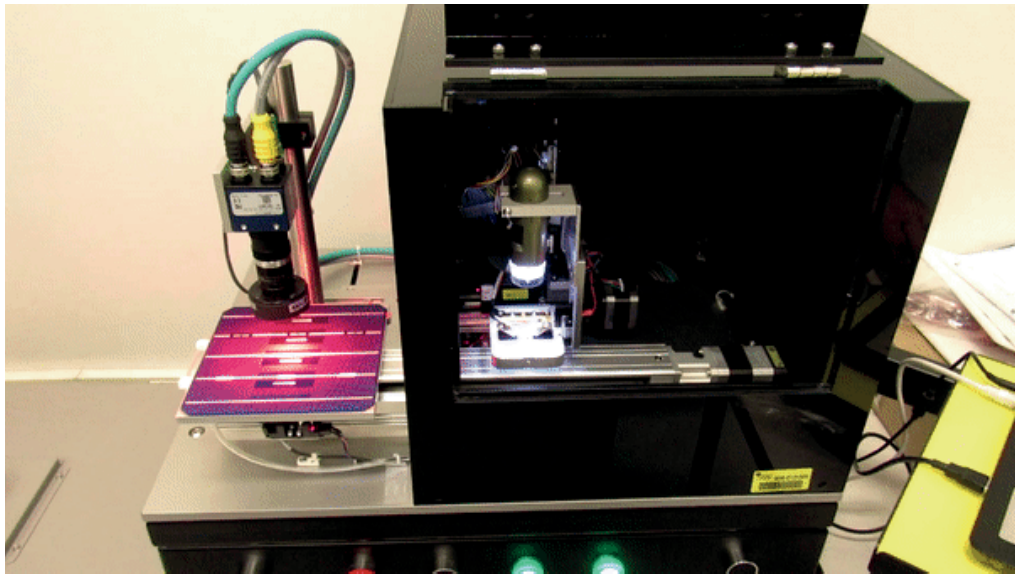
Conclusion

- Demonstrated a non-destructive measurement of ρ_c on commercial grade solar cells
- cTLM structures integrated into busbars do not compromise efficiency or aesthetics
- ContactSpot-PRO allows for fast and automated measurement of R_{sheet} and ρ_c



Thanks!

- Team
  - University of Central Florida
  - BrightSpot Automation
  - Foshan University
  - Gonda Electronic Technology
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