NREL
NATIONAL RENEWABLE ENERGY LABORATORY

How [NOT] to Measure a Solar Cell to Get the Highest Efficiency

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Session 13

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Approach

- **Follow techniques in the literature or observed that artificially Enhance the Efficiency**
- **Efficiency = 100* Power Out / Power In**
  - Temperature unspecified
    - Measure as low as possible until freeze out to get the maximum voltage
  - Spectrum unspecified - Maximize photocurrent by using a single wavelength near the energy gap
    - Efficiency >70% reported in the literature for GaAs
  - Total irradiance - unspecified so pick the irradiance that gives the maximum efficiency
    - CPV cell efficiencies already do this

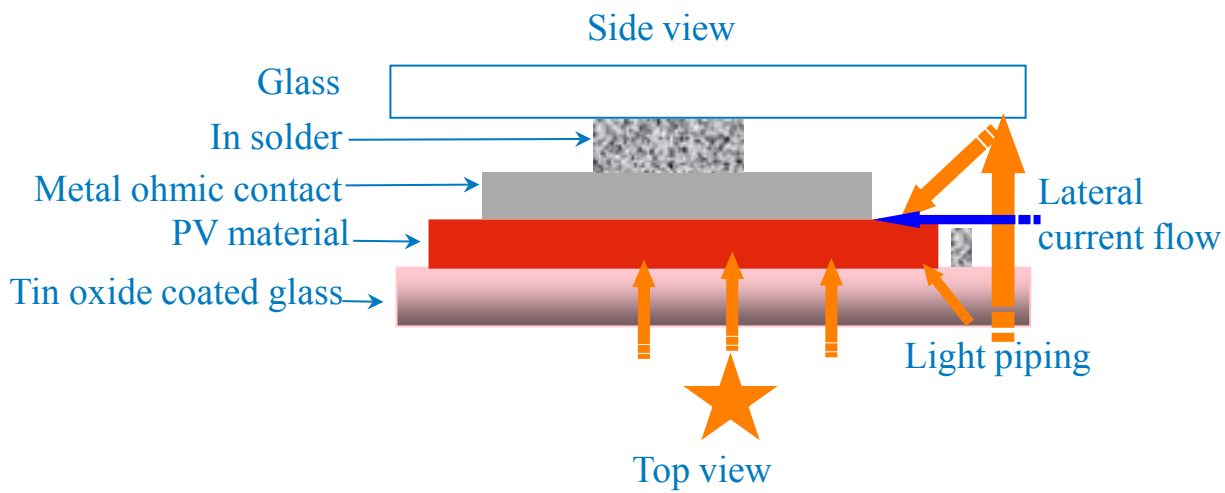
Areas of Enhancement

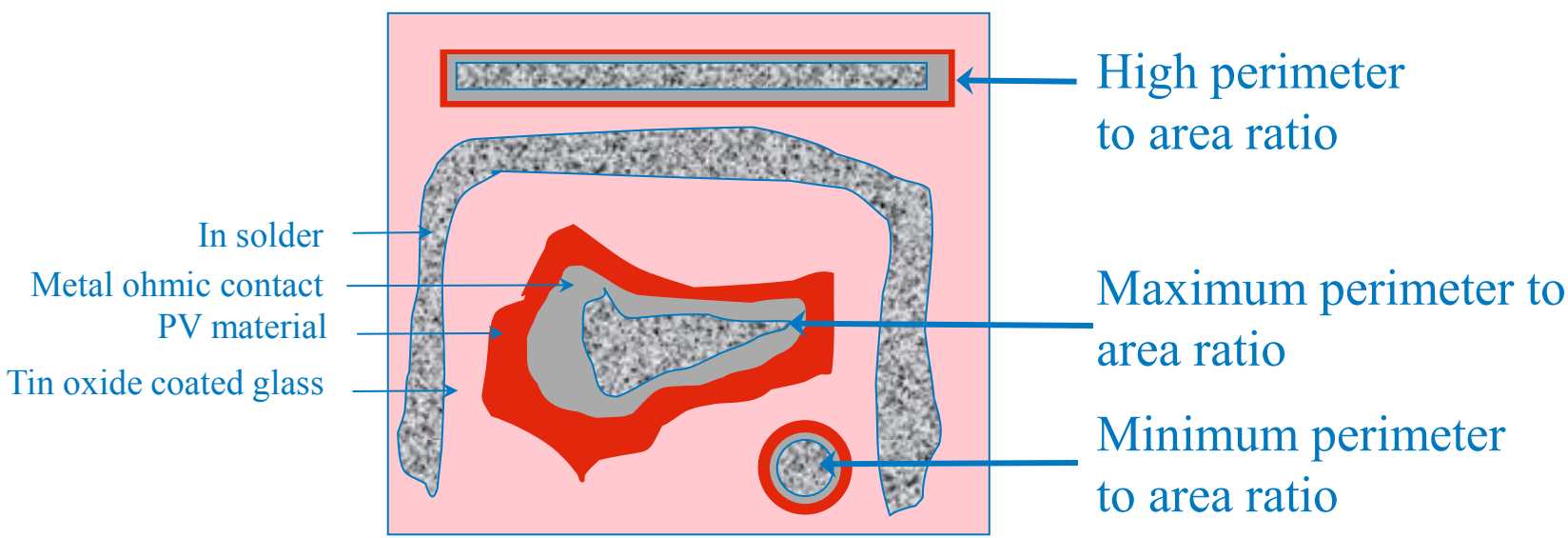
- **Photo-current**
  - Small Area - large perimeter to area ratio enhances
    - Light piping
    - Collection outside the edge of the cell
  - Spectral Error
    - Use a thermal detector to maximize spectral error or poorly matched reference cell
  - Simulator Enhancement
    - Artifact associated with low cost simulators
    - Wear white lab coat and stand near sample when testing but not when setting light level.

Areas of Enhancement - continued

- **Photo-current**
  - Irradiance measurement
    - Poorly calibrated detector
  - Maximize TCO transmittance at the expense of sheet resistance which can be dealt with in optimizing the fill factor
  - Use zero shading probe to simulate a zero shading ribbon (accepted procedure by NREL& Fraunhofer ISE for Si cells)
  - Poor cell isolation allowing adjacent cells to contribute current without being part of the area

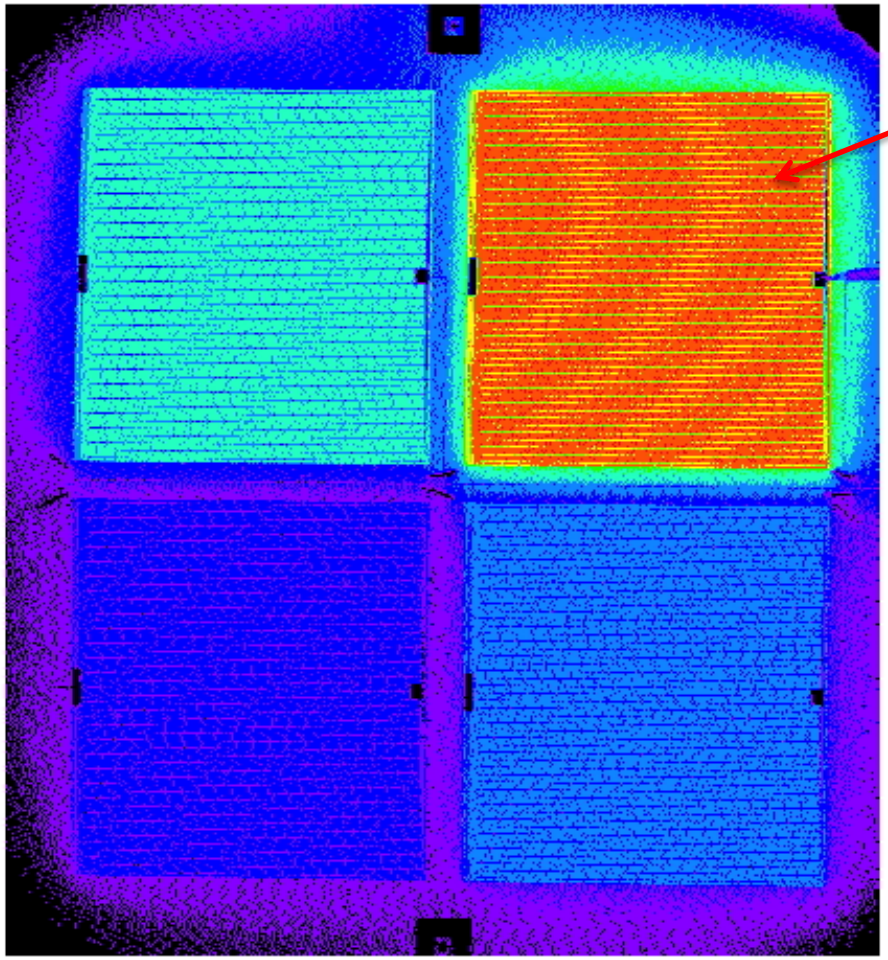
Small Cell Area



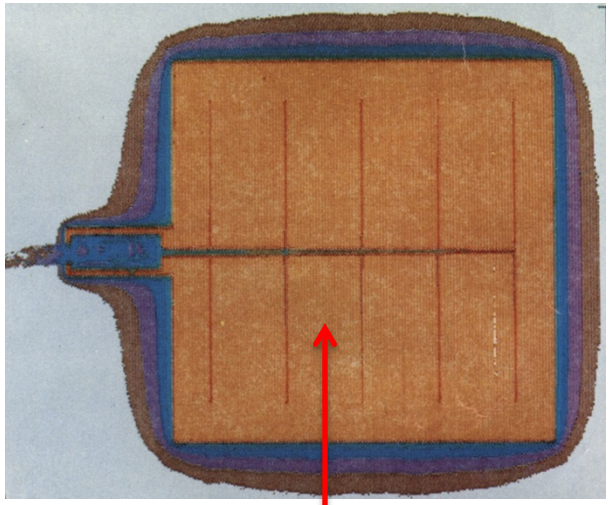


Incomplete Mesa Isolation

Laser Scans showing current collection outside the defined area of the cell



Only this cell of the 4 silicon cells on a silicon wafer should show a response



According to customer only the orange region is active.

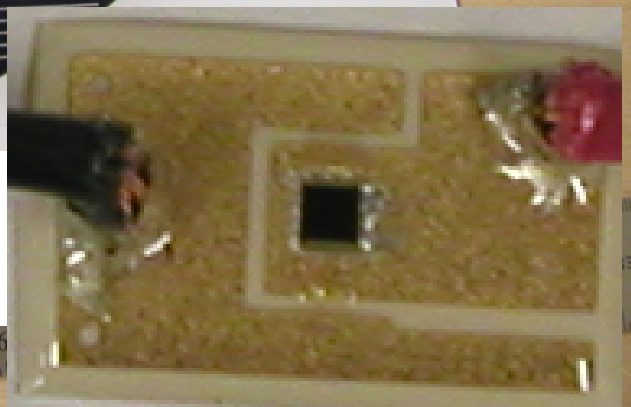
C.R. Osterwald and K.A. Emery, "Solar Cell Area Considerations," Solar Cells, vol. 10, 1983, pp. 1-5.

Light trapping

30% Enhancement!!

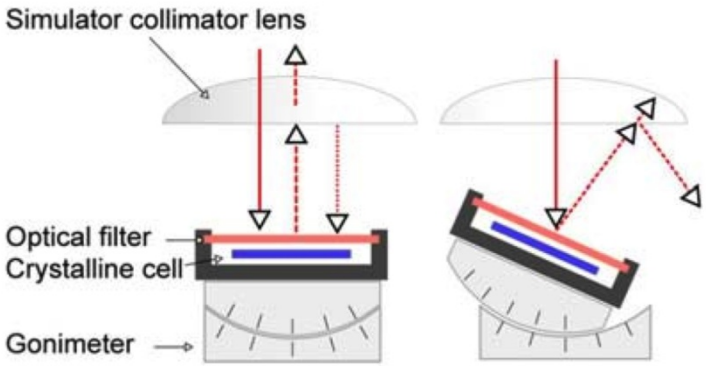
Aperture area, cm^2	Border mm	Voc mV	Isc A	FF %	Efficiency
unmasked	--	603.3	1.346	60.63	14.1
82.8	32	602.4	1.298	61.39	13.7
64.0	21	601.7	1.265	61.36	13.3
51.8	13	600.8	1.222	61.86	13.0
37.2	2	597.8	1.147	62.39	12.2
34.8	0	597.8	1.095	62.95	11.8

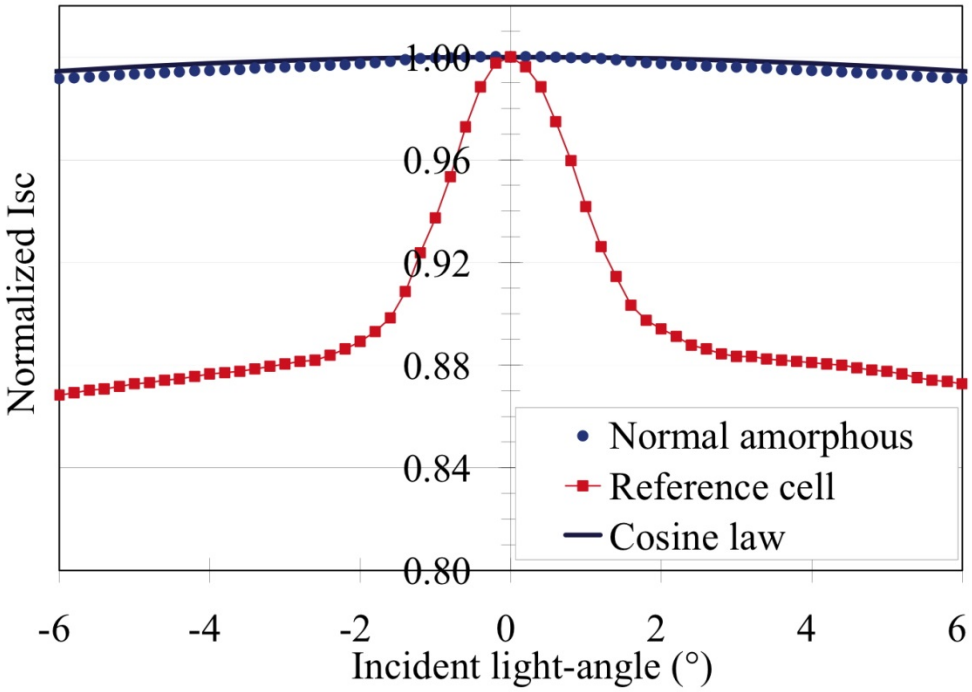
30% boost in Isc from light outside cell area because cell coated with silicone



Simulator based Enhancement

- **Spatial nonuniformity**
  - Place reference device in region with lowest irradiance and test device in region with highest irradiance.
- **Internal reflections**

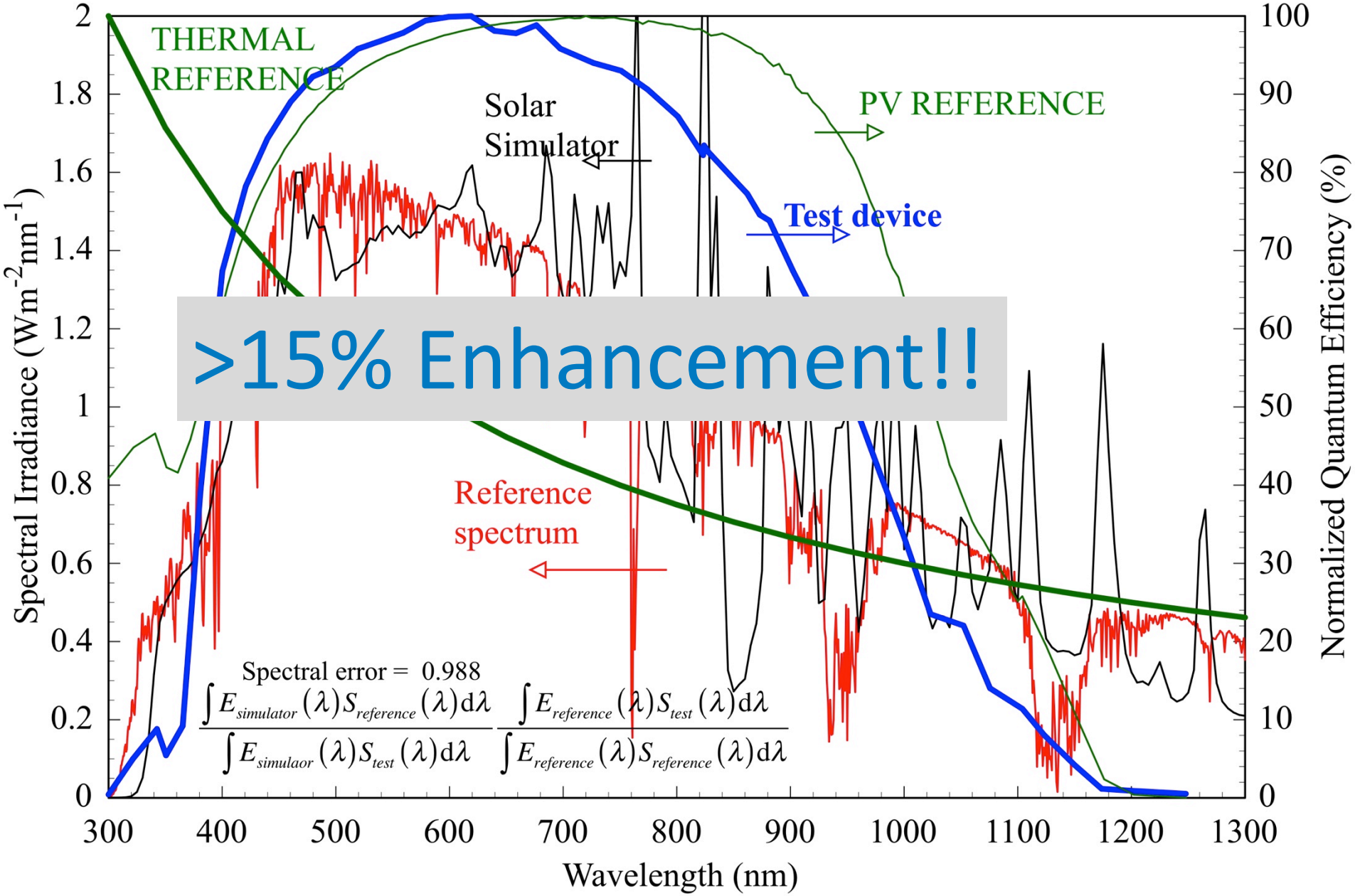




D. Romang, J. Meier, R. Adelhelm, U. Kroll,"**Reference Solar Cell Reflections In Solar Simulators**," 26th EU PVSEC

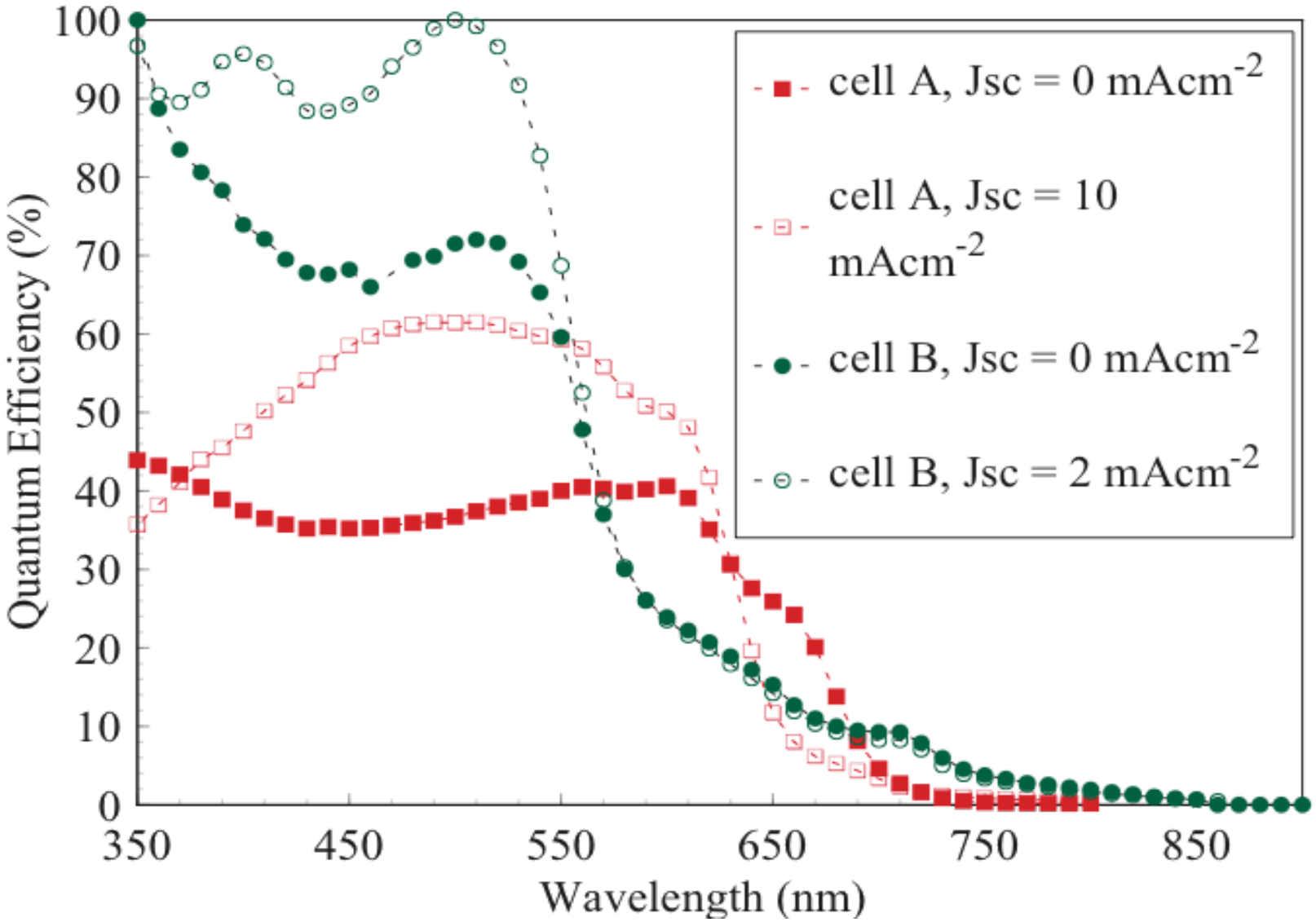
K. Morita, S. Kera, S. Kiehn, **Measurement Error and Solution Due to Reference Cell's Structure,"** 21st International PVSEC 11/28- 12/2, 2011, Fukuoka, Japan

SPECTRAL ERROR



>15% Enhancement!!

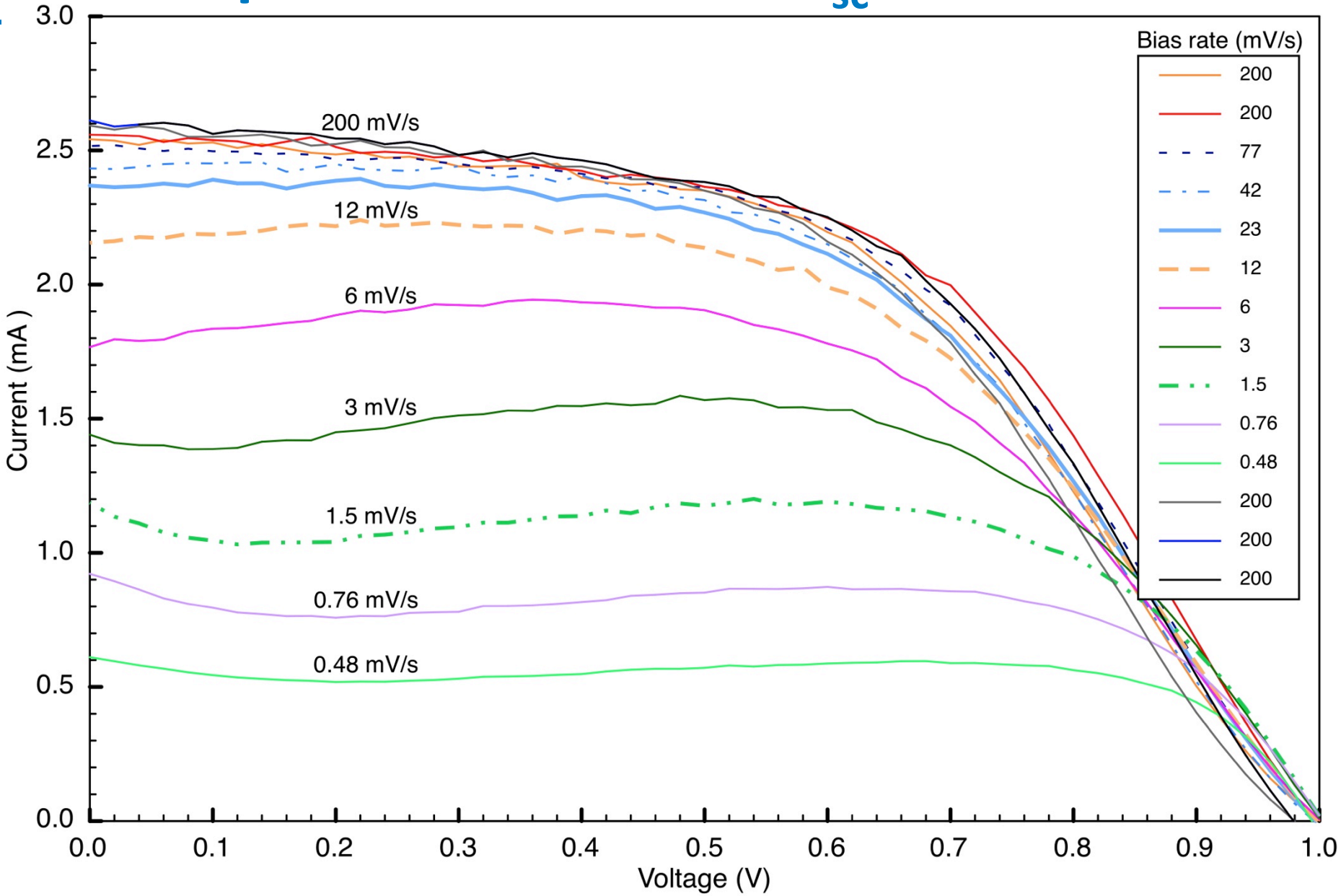
QE bias light effect



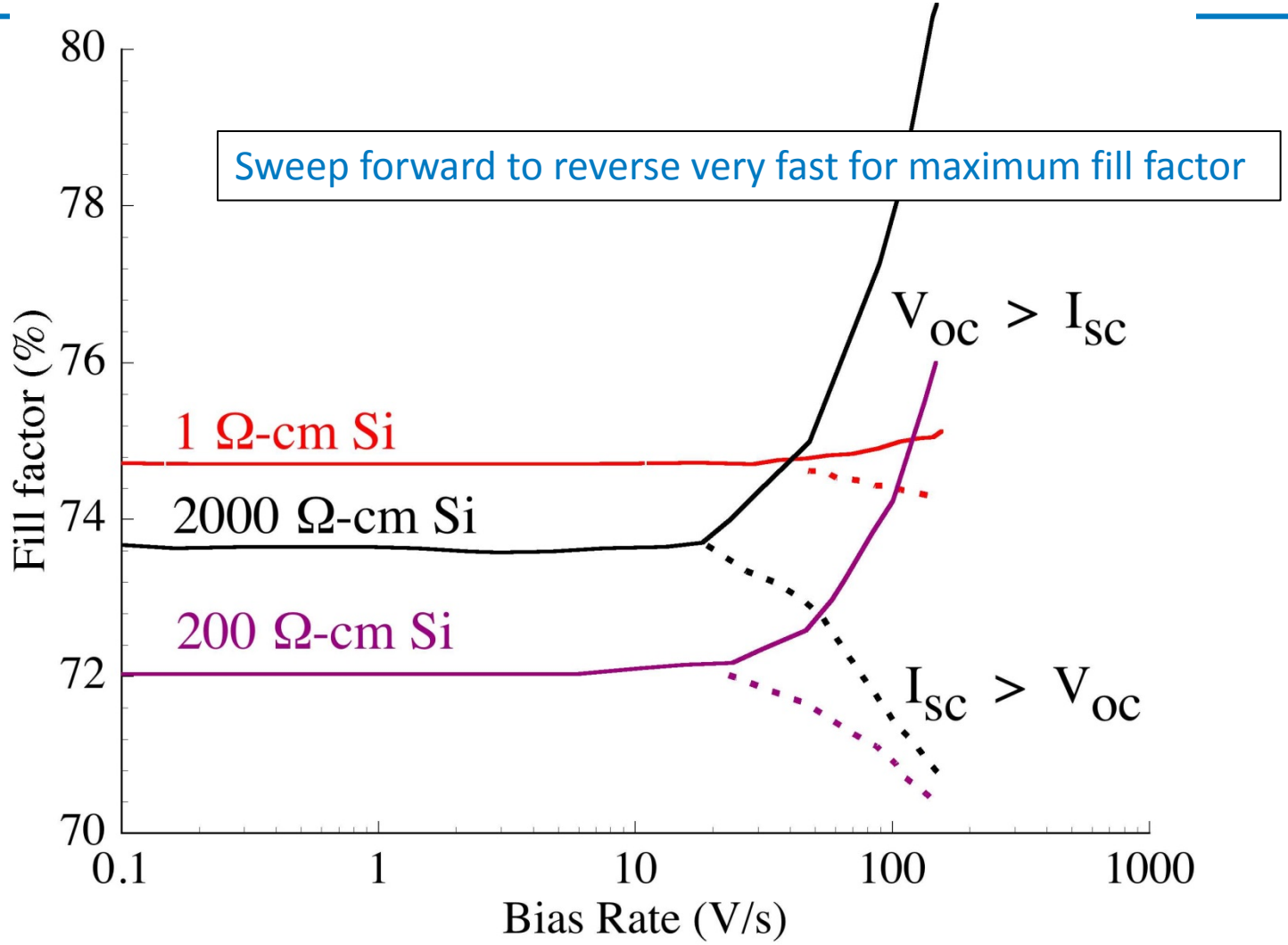
Fill Factor Enhancement

- **Now that the photocurrent is optimized -**
- **Knobs at your disposal for FF enhancement**
  - Maximize Voltage bias rate and sweep forward to reverse
  - Maximize number and surface area of current contacts (current procedure for silicon cells)
  - Separate voltage from current contact. The potential moves towards Voc as the distance between the contacts increases. (Put the voltage probe on the end of a grid finger.)
  - Lower the temperature (~0.5%/°C)
  - Adjust the light level
  - Minimize sheet resistance impact by injecting current everywhere

Sweep fast for maximum I_{sc} for this cell



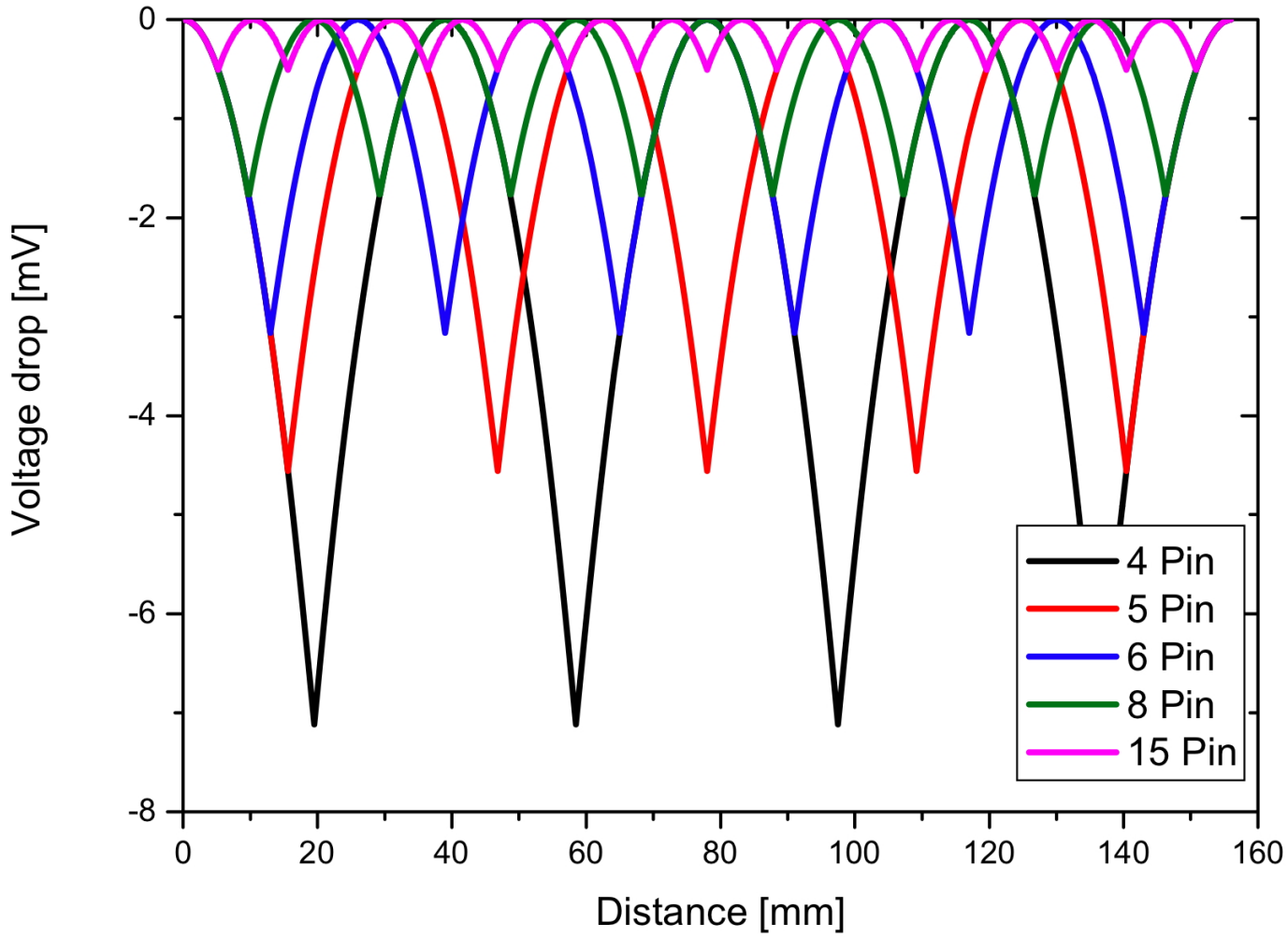
Bias rate & direction



D.L. King, J.M. Gee, and B. R. Hansen, "Measurement Precautions for High-Resistivity Silicon Solar cells," proc. 20th IEEE PVSC, 1988, p. 555.

Probe Spacing

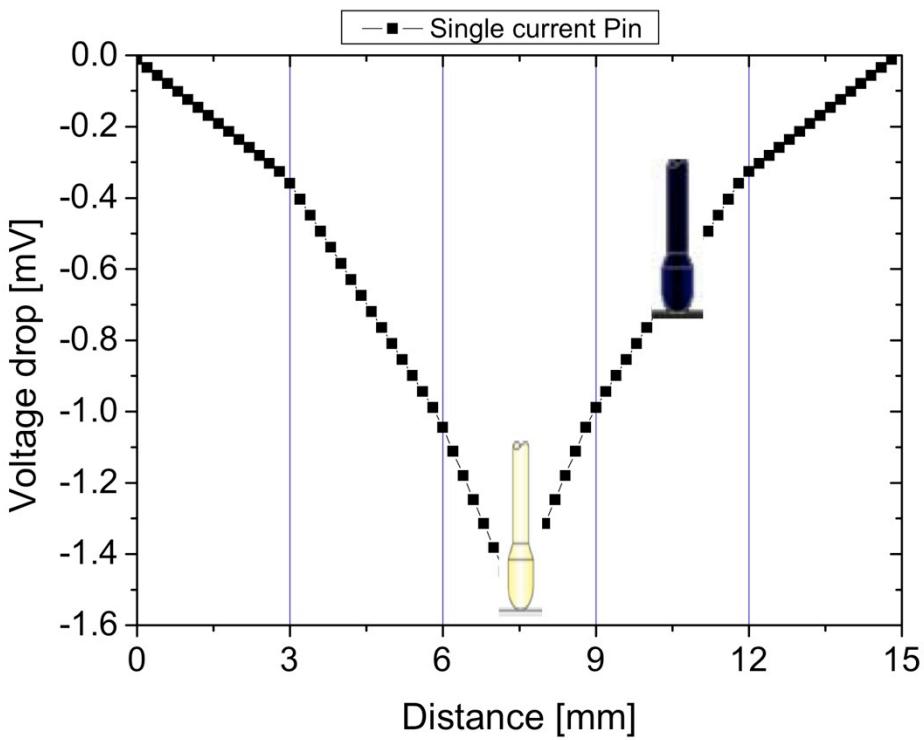
More current contact points means lower voltage drop & higher fill factor

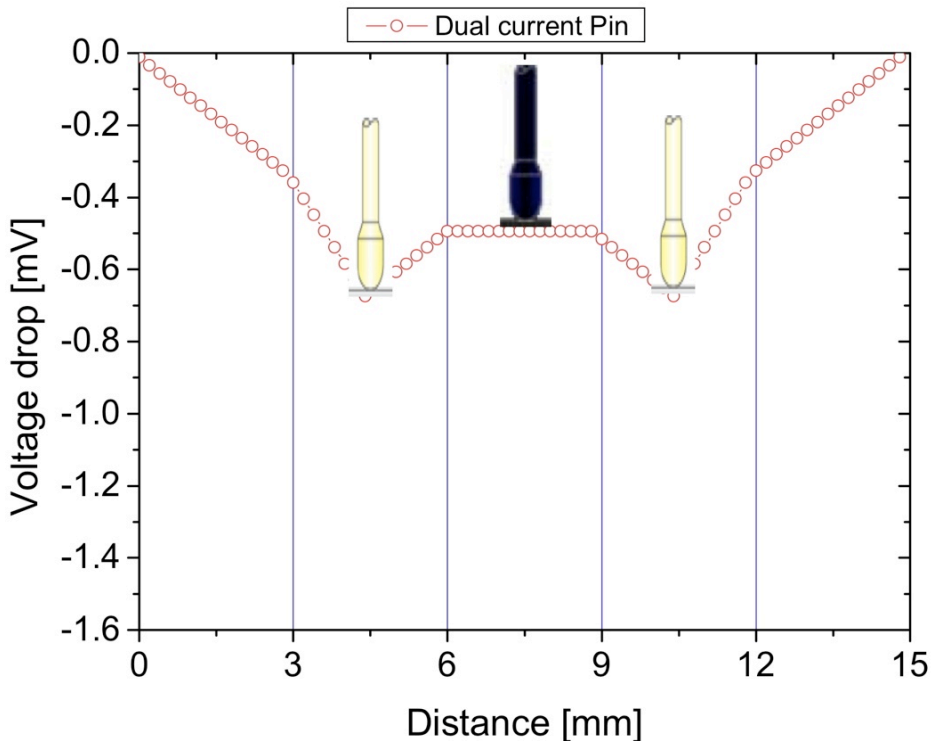


J. Hohl-Ebinger, D. Grote, B. Hund, A. Mette, W. Warta, "Contacting Bare Solar Cells For Stc Measurements," 23rd European Photovoltaic Solar Energy Conference, 1-5 September 2008, Valencia, Spain

Contacting - single vs. dual current

Simulate zero sheet resistance (**superconducting**) bus bar

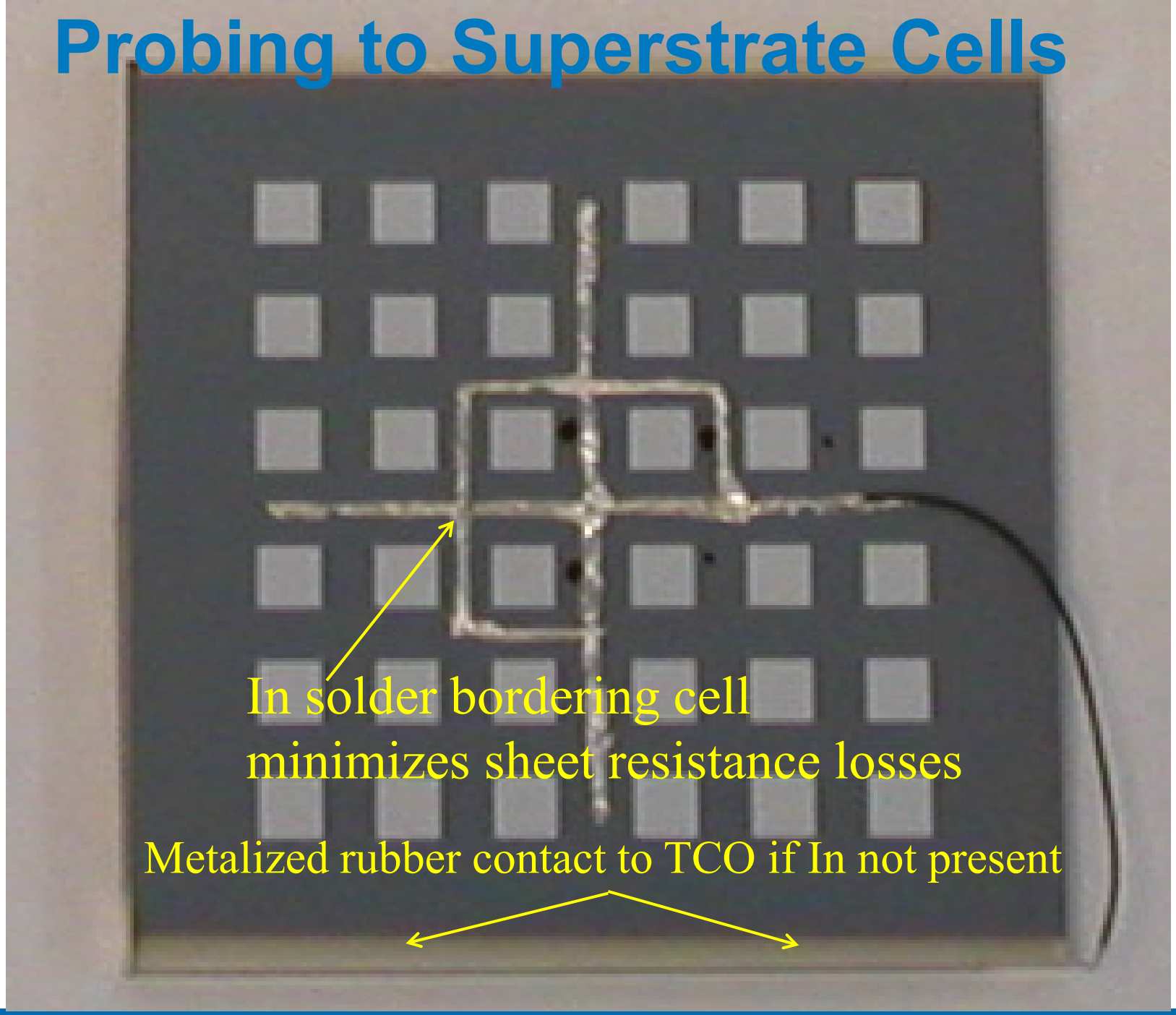




Potential distribution for a single current pin and a dual current pin with a period of 15 mm. Distance to the voltage pin 3 mm. Current pins are yellow and voltage pins are black.

J. Hohl-Ebinger, D. Grote, B. Hund, A. Mette, W. Warta, "Contacting Bare Solar Cells For STC Measurements," 23rd EU PVSEC, 2008, Valencia, Spain

Probing to Superstrate Cells



Other tricks of the trade

- **Take advantage of metastability and "charge up" transient states by forward biasing past Voc, or applying a positive or negative static charge to the surface.**
- **Trade off stability for efficiency. Operate an electrochemical cell as a battery and consume the electrodes for improved efficiency.**
- **Test before any photon or other initial irreversible degradation.**

K. Emery and H. Field, "Artificial Enhancements and Reductions in the PV Efficiency," 24th IEEE PVSC, p. 1833, 1994.

Summary

- **Following the guidance you can achieve any efficiency you want based upon**

  power out /power in
- **Small area cells make it easier to enhance the photocurrent**
- **Separating the voltage sense and the current contact will always help**
- **There is an inherent operator bias to discard procedures that give lower efficiencies even if they are more 'correct'.**