



Engineering Laboratory

PV Electrical Characterization Metrology at NIST

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NIST campus in Maryland near Washington DC



- A National Laboratory of the U.S. Department of Commerce
- 3,000 employees
- 2,800 associates and facilities users
- 1,300 industrial partners
- \$864 million annual budget (2015)
- Two main campus: Gaithersburg, MD and Boulder, CO.
- National measurement standards
- Large-facility infrastructure:
 - NIST Center for Neutron Research
 - Center for Nanoscale Science and Technology
 - Synchrotron Measurement Science Group



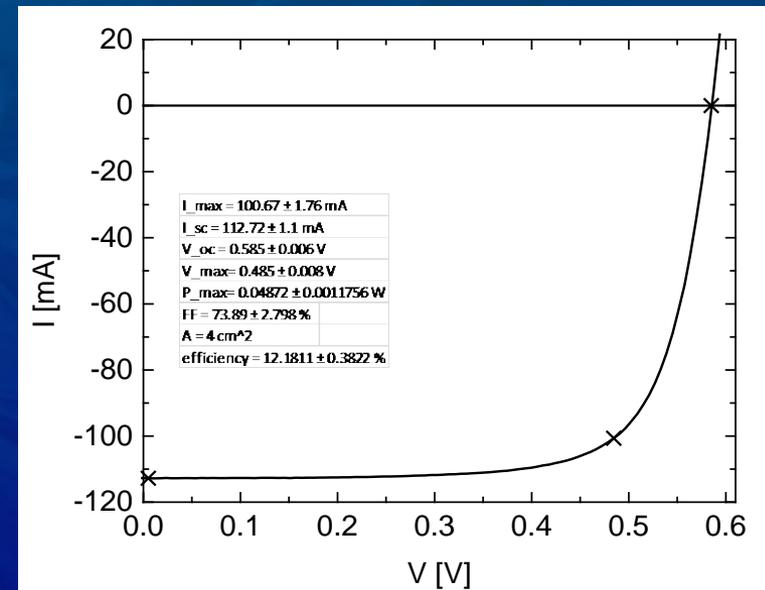
Established 1901



PV Testing Methodology

For testing performed under a solar simulator, issues to consider are:

- Quality and rating of the solar simulator
 - Spectral irradiance match to the STC (AM 1.5)
 - Uniformity of the illumination
 - Temporal stability of the light source
- Spectral responsivity and calibration of a reference cell
- Spectral responsivity of the test cell or module.
- Determination of a spectral mismatch factor, M .
- Linearity of cell response with irradiance.
- Current-voltage (I-V) measurements of the device.
- Correction of the I-V curve using M , temperature, irradiance fluctuations etc.
- Determination of the module parameters, including power conversion efficiency and power rating.



Conventional Solar Simulators

Flash module simulator



- IEC Standard 60904-9 Class AAA Simulator
- Spectral match: 0.75-1.25 for 6 wavelength-intervals
- Irradiance non-uniformity: $\leq \pm 2\%$
- Irradiance temporal instability: $\leq \pm 2\%$
- Flash Plateau: 36 ms
- IV scan interval: ≤ 1 ms
- Variable scan delay : 1 – 12 ms
- Irradiance Range: $\sim 500 - 1100$ W/m²
- Maximum irradiated area: 2.4 m diagonal
- Spectral composition filter

Steady-state cell simulator



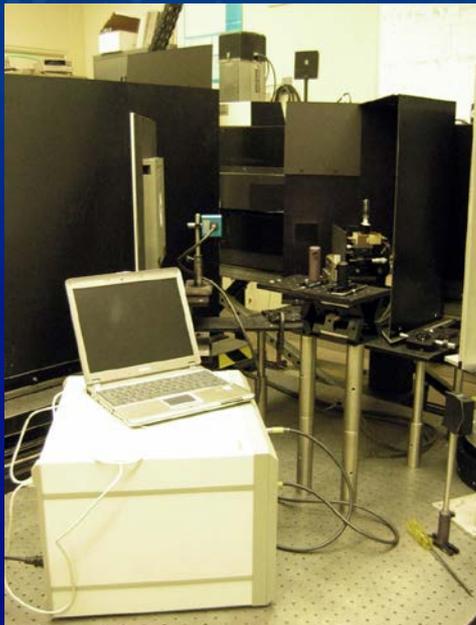
- Class AAA, Xe-based solar simulator
- Illumination area of 156 x 156 mm
- Irradiance range: 50-1200 W/m²
- Special concentrator optics for 10x and 100 x illumination intensities
- Rotatable side or downward illumination



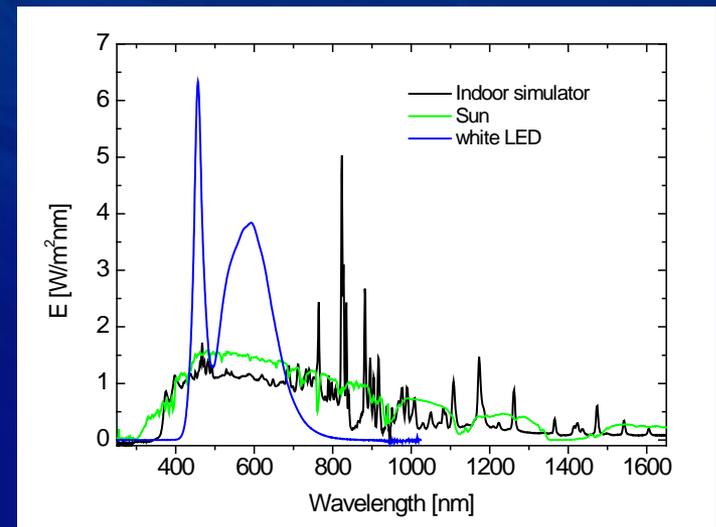
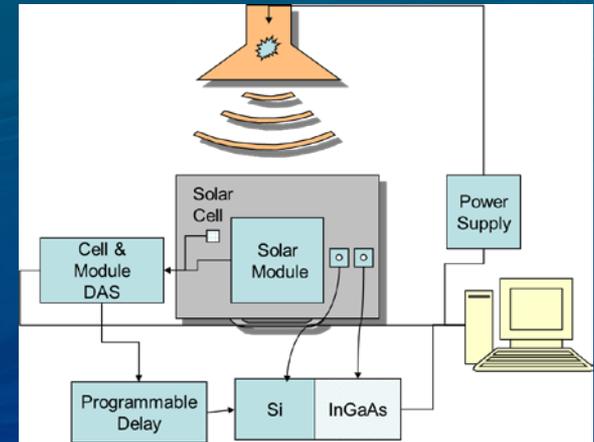
Spectral Irradiance Measurements

- Any indoor light source should be spectrally measured.
- We use calibrated spectroradiometers.
- FEL lamps with direct traceability to NIST cryogenic Radiometer are used.

Radiometer calibration facility



NIST 1000 W FEL lamps

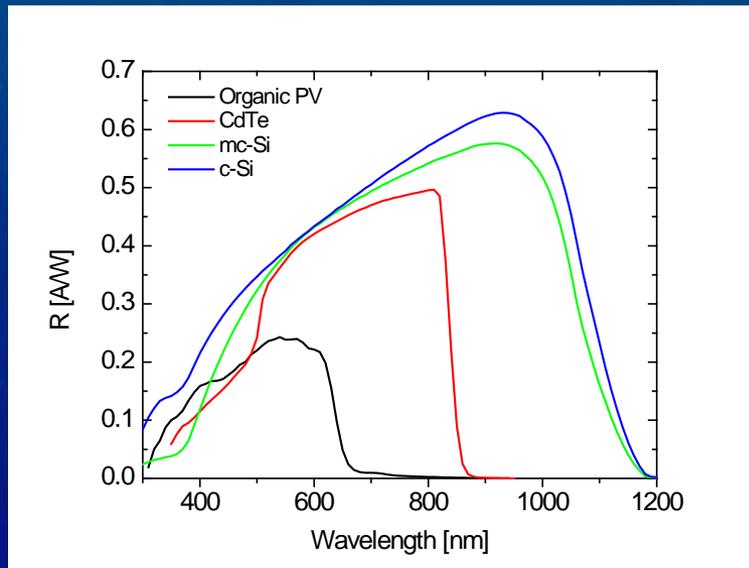


Spectral Responsivity (SR)

Solar cell spectral responsivity $R(\lambda)$: The measurement of the wavelength dependence of the photocurrent relative to:

1. The **irradiance** of the incident radiation (**irradiance SR**, $R_{irrd}(\lambda) = I_{ph}(\lambda)/E(\lambda)$)
2. The **power** of the incident beam (**power SR**, $R_{pwr}(\lambda) = I_{ph}(\lambda)/P(\lambda)$)

Power Spectral responsivity of some PV technologies

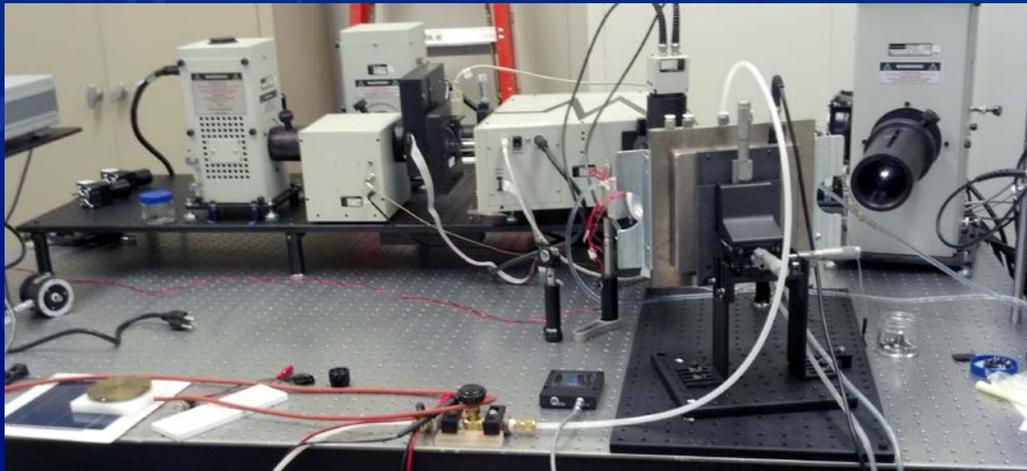
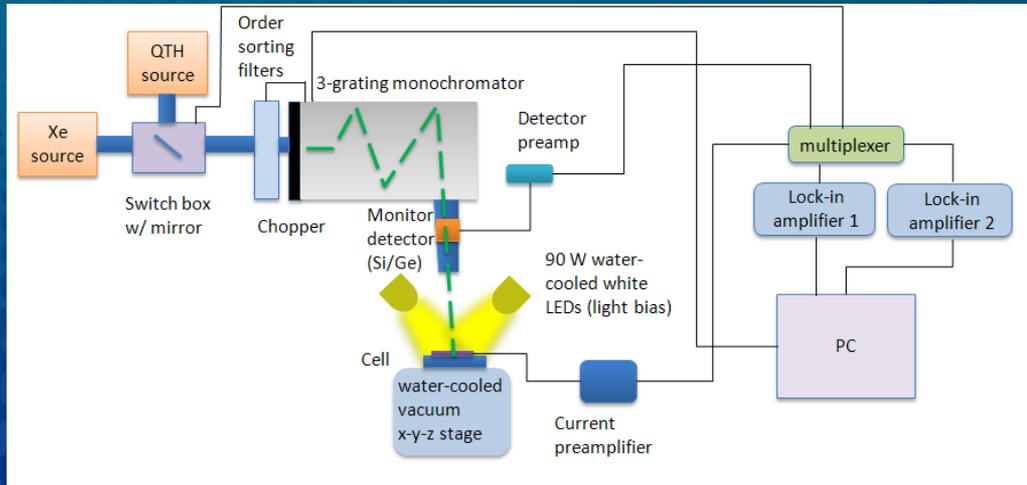


- Essential for solar cell efficiency and rating certification under STC.
- SR varies among different cell technologies.
- SR is a fundamental PV characterization technique.



Spectral Responsivity Measurements

Monochromator-based (beam underfilling cell)



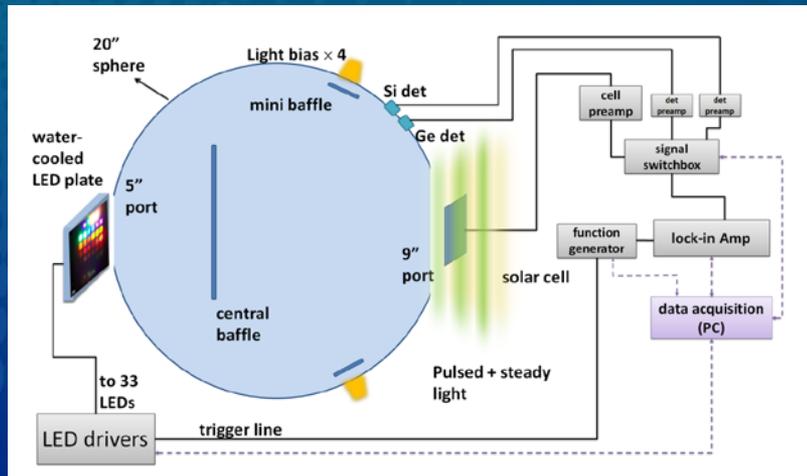
Unique features:

- Dual Xe and QTH light sources
- Improvements in signal to noise
- 300 nm -2500 nm measurement range
- Custom DC+AC preamplifier handling up to 1.6 A of DC
- Light bias illumination of 200 cm² area
- Allow two lock-in measurements synchronously.
- Fully controlled and automated
- Capability to perform multi-junction solar cell measurements



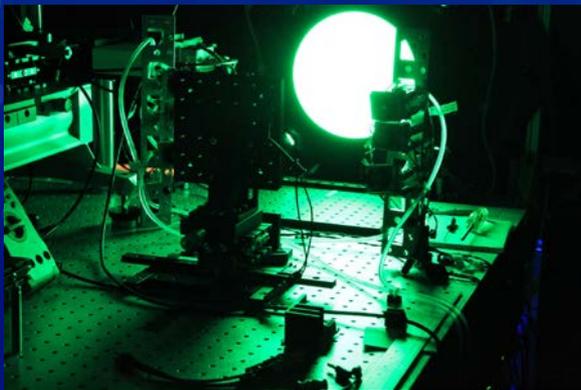
Spectral Responsivity Measurements

LED integrating sphere-based (beam overfilling)



Sphere characteristics:

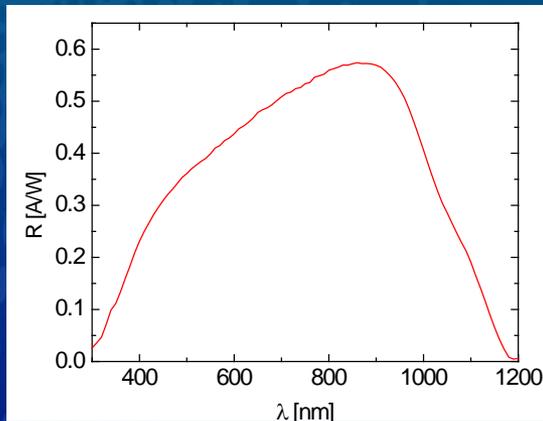
- Sphere diameter of 50.8 cm, with a 12.7 cm rear port and a 22.9 cm exit port
- 2 ports for monitor photodiodes (Si and Ge)
- 4 ports for coupling in bias light
- Central baffle for improving light uniformity
- 33 pulsable LEDs coupled in through the rear port
- All LEDs are water-cooled
- Commercial LED drivers, triggered by a function generator run the LEDs sequentially
- Illumination of DUT can be either diffuse (no collimator) or collimated with a lens assembly at the exit port.
- Lock-in technique for data collection
- In-house Labview program



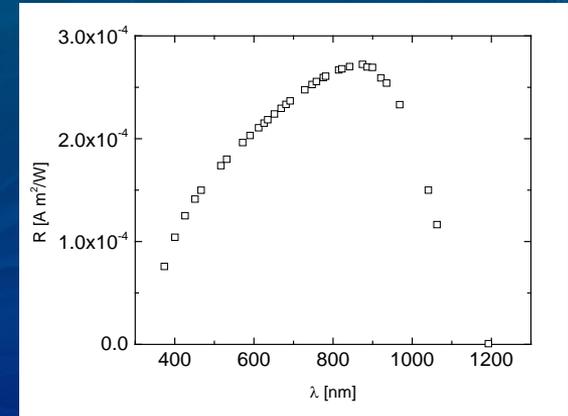
NIST Procedure

Objective: Obtain the irradiance spectral response of entire cell

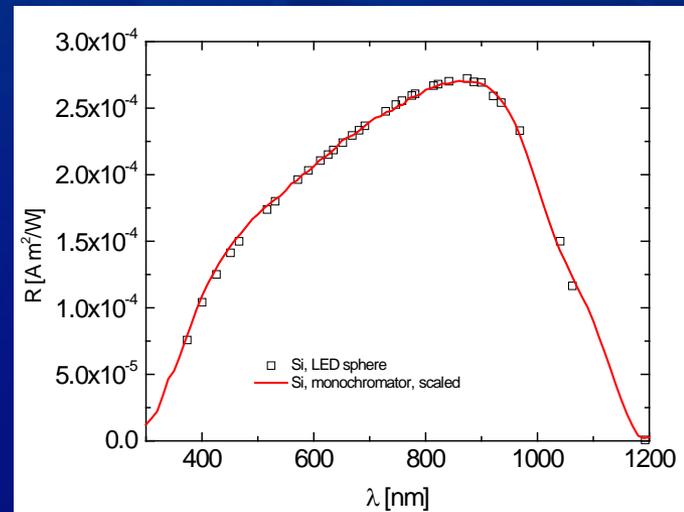
(1) Obtain the power-mode SR with the monochromator



(2) Using LEDs in overfill illumination mode, obtain irradiance SR data points at select wavelengths

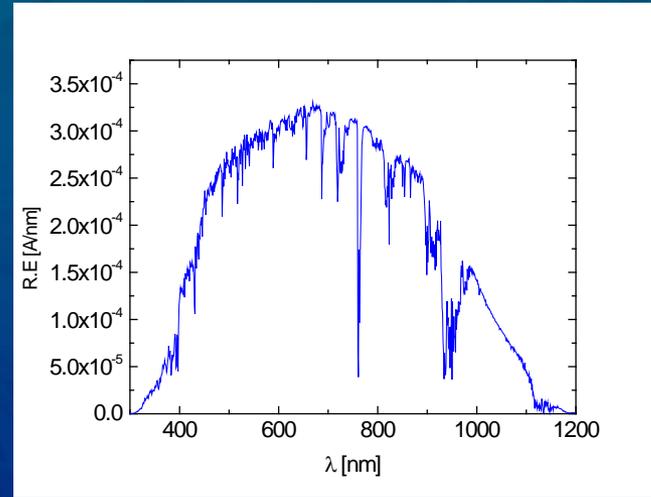
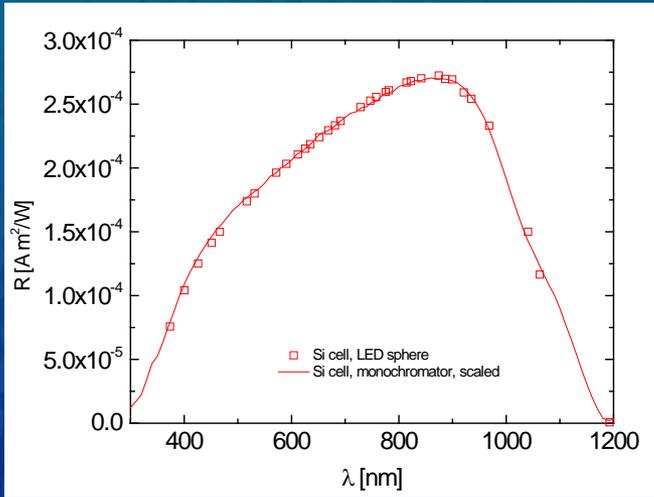


(3) Fit the power curve to the LED based irradiance data



Primary Cell Calibration

Only irradiance-mode SR can be used reliably for I_{sc} calculations



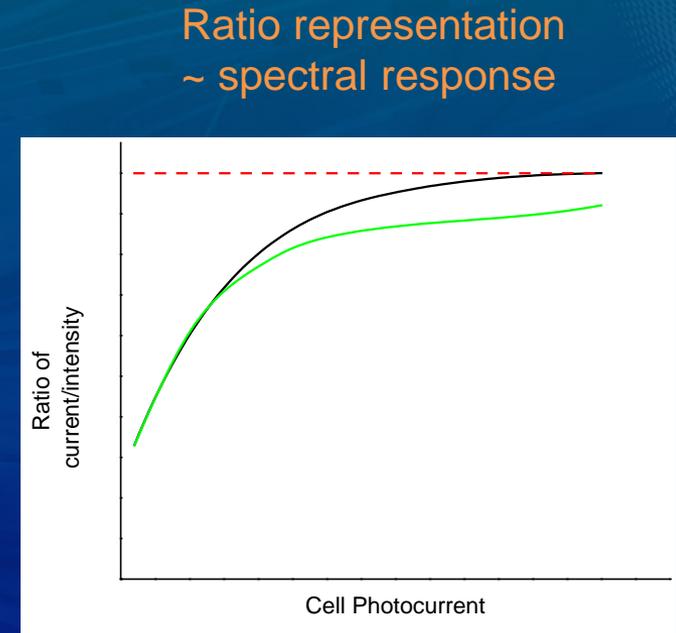
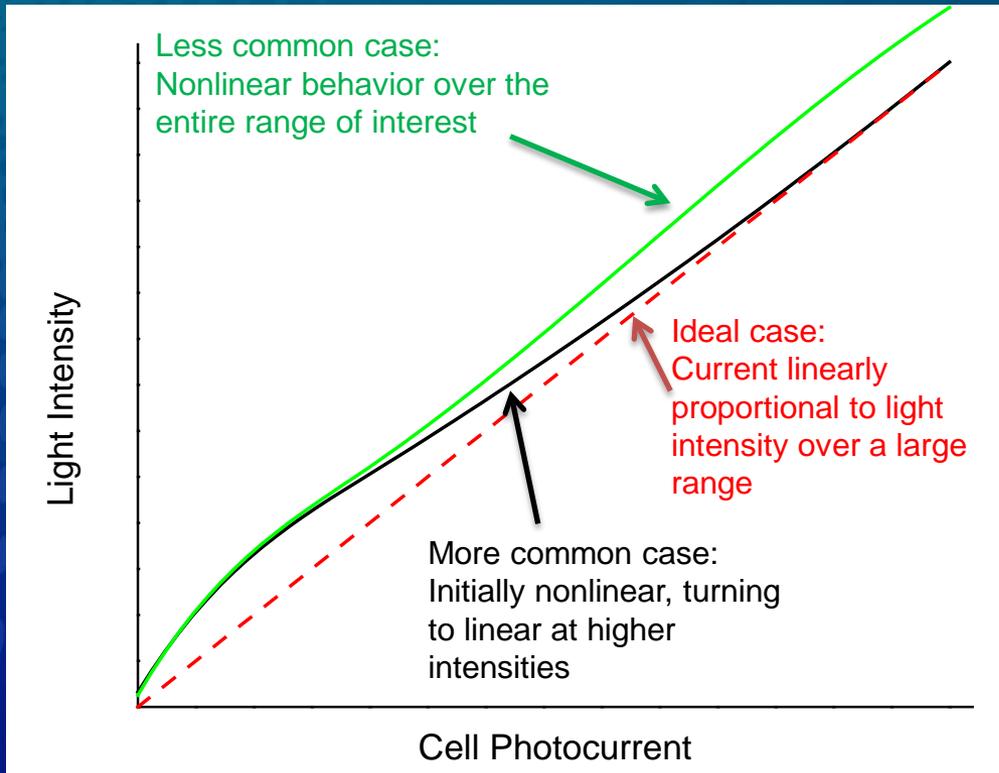
$$I_{sc} = \int R(\lambda) \cdot E(\lambda) d\lambda = 160.24 \text{ mA}$$

Intercomparison measurements

Cell ID	I_{sc} [NIST measurement]	Other Laboratory	I_{sc} [Other Laboratory]	Percent Difference
NIST 189	112.49 ± 1.03 mA	NMC-Singapore	112.08 ± 1.0 mA	0.36 %
VLSI10540-0144	134.2 ± 1.02 mA	VLSI Standards	134.3 ± 1.9 mA	0.074 %
US1	10.02 ± 0.076 mA	NREL	9.9985 ± 0.09099 mA	0.21 %
RR232KG5	61.57 ± 0.49 mA	Rera Systems	61.1 mA	0.8 %
NIM 116	123.57 ± 1.18 mA	NIM-China	122.49 ± 1.10 mA	0.87 %



Nonlinearity of Photocurrent with Irradiance in Si Solar Cells



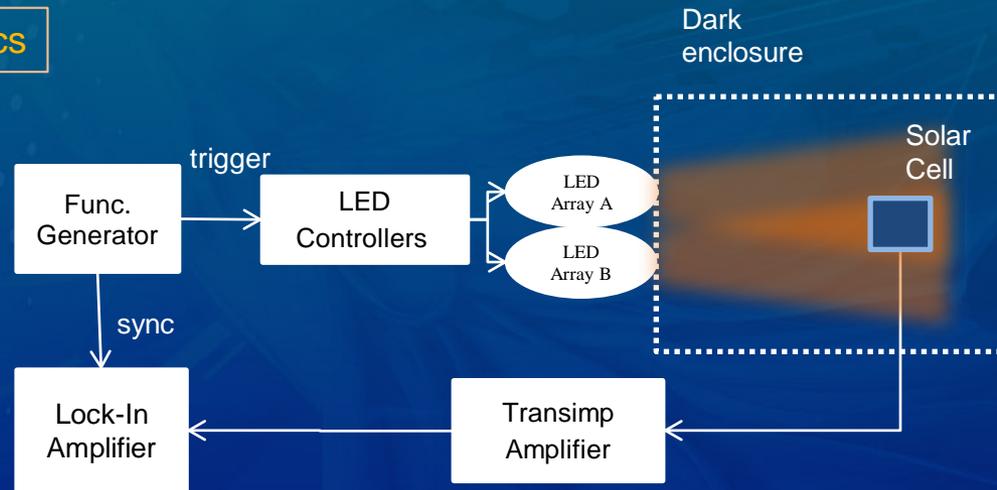
- Si solar cells are usually nonlinear at low light (~ 1 % sun) conditions.
- Cell transitions from nonlinear to linear regime at > 5 % sun intensity.
- Notable exceptions have been observed, in rare cases.
- Nonlinear behavior is spectral dependent.



Combinatorial LED-based Technique

Method: An LED-based apparatus, based on the concept of combinatorial flux addition (superposition) to measure PV solar cell nonlinearity response

Schematics



Combinatorial Algorithm

LED A current schedule	LED B current schedule
X1	Y1
X2	Y2
X3	Y3
X4	Y4
X5	Y5
X6	Y6
X7	Y7
X8	Y8
X9	Y9
X10	Y10
X11	Y11
X12	Y12
X13	Y13
X14	Y14
X15	Y15

Combinatorial analysis

Flux: ϕ
Signal: s

Polynomial of N^{th} degree

$$\phi = g(s) = r_0 + r_1s + r_2s^2 + \dots + r_Ns^N$$

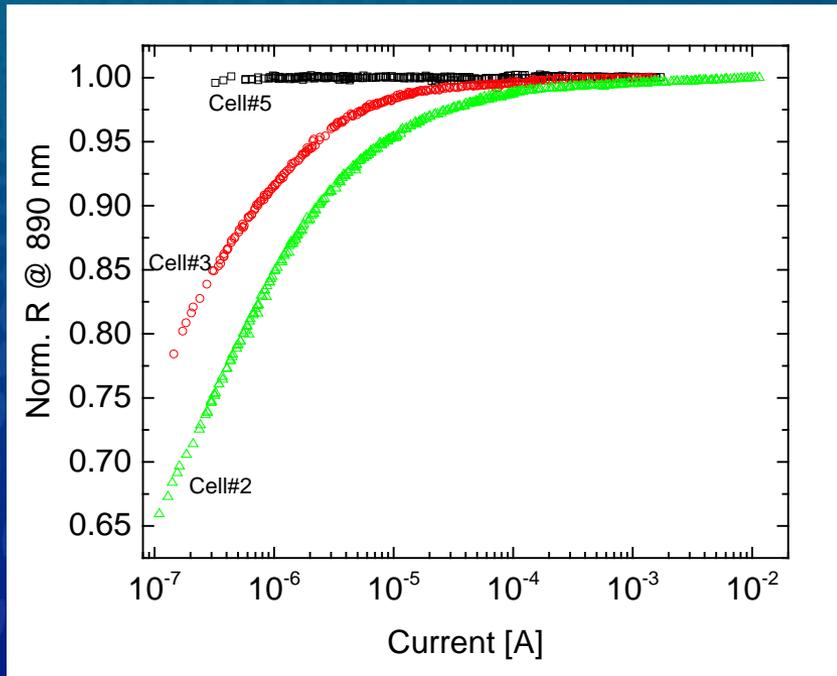
- Construct an overdetermined linear system of equations
- Solve for unknown fluxes, ϕ , by least square fit
- Check residuals

$$\left\{ \begin{array}{l} 0 = r_0 + r_1s_{A_1} + \dots + r_Ns_{A_1}^N - \phi_{A_1}, \\ \vdots \\ 0 = r_0 + r_1s_{A_{K_A}} + \dots + r_Ns_{A_{K_A}}^N - \phi_{A_{K_A}}, \\ \vdots \\ 0 = r_0 + r_1s_{B_1} + \dots + r_Ns_{B_1}^N - \phi_{B_1}, \\ \vdots \\ 0 = r_0 + r_1s_{B_{K_B}} + \dots + r_Ns_{B_{K_B}}^N - \phi_{B_{K_B}}, \\ \vdots \\ 0 = r_0 + r_1s_{A_i+B_{j_i}} + \dots + r_Ns_{A_i+B_{j_i}}^N - \phi_{A_i} - \phi_{B_{j_i}}, \\ \vdots \\ 0 = r_0 + r_1s_{A_{i_M}+B_{j_M}} + \dots + r_Ns_{A_{i_M}+B_{j_M}}^N - \phi_{A_{i_M}} - \phi_{B_{j_M}} \end{array} \right. \left. \begin{array}{l} K_A \text{ eq's} \\ K_B \text{ eq's} \\ M \text{ eq's} \end{array} \right.$$

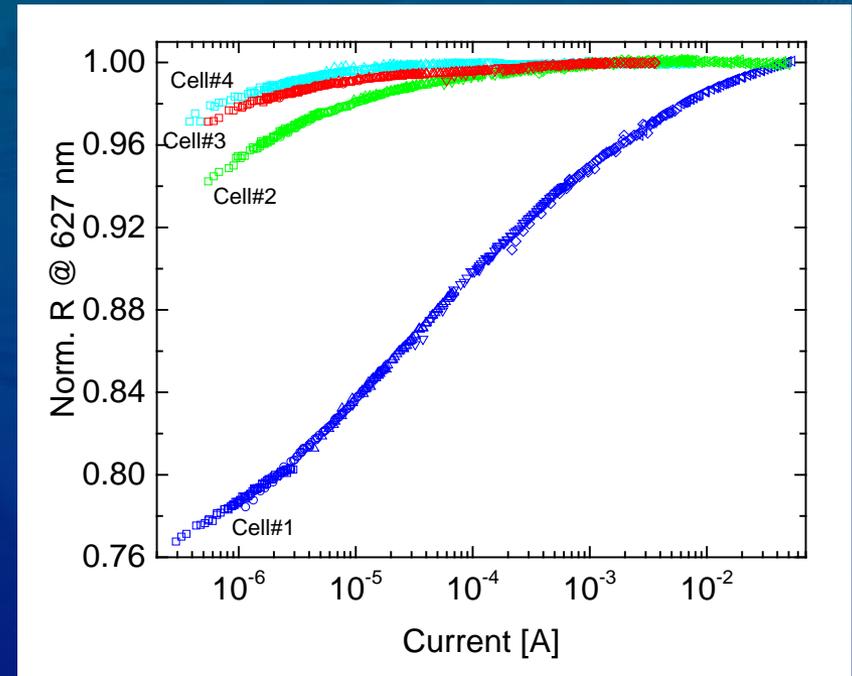


Si Cells' Behavior

$\lambda = 890 \text{ nm}$



$\lambda = 627 \text{ nm}$

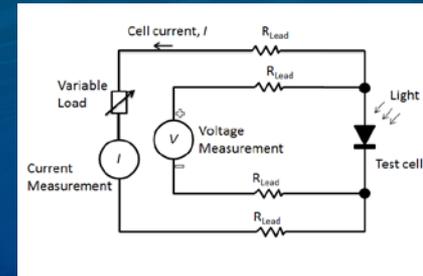
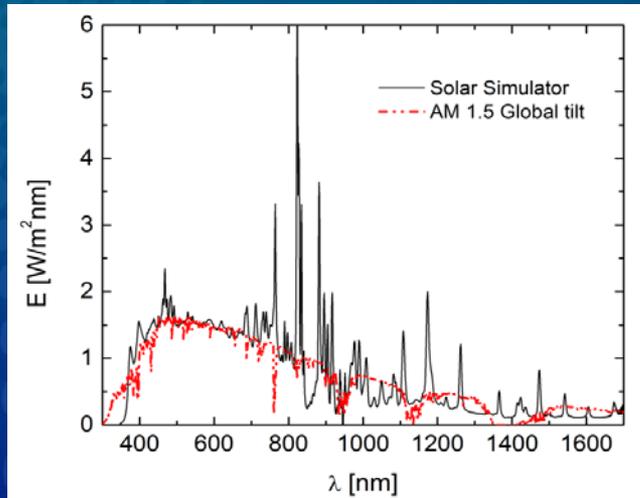


- Comparing the ratio, $R=s/\phi$ for 5 different types of Si solar cells
- Cell#5 is purely linear.
- Two have some degree of nonlinearity at low signal levels
- Cell#1 (KG5-filtered Si cell) remains nonlinear even at high current/intensity levels.



I-V Measurements and Issues

Measurements should be reported under SRC, i.e, AM 1.5 G spectrum, 25 °C etc



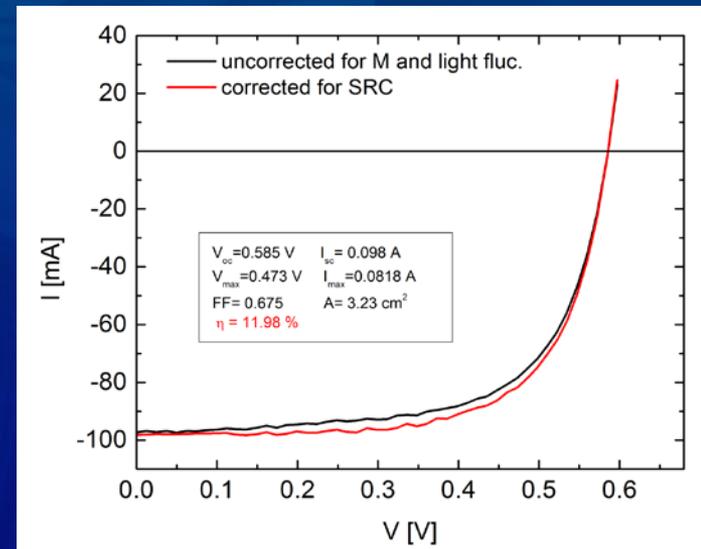
$$M = \frac{\int_{\lambda 1}^{\lambda 2} E_s(\lambda) R_t(\lambda) d\lambda}{\int_{\lambda 3}^{\lambda 4} E_s(\lambda) R_r(\lambda) d\lambda} \times \frac{\int_{\lambda 2}^{\lambda 3} E_r(\lambda) R_r(\lambda) d\lambda}{\int_{\lambda 1}^{\lambda 2} E_r(\lambda) R_t(\lambda) d\lambda}$$

Spectral mismatch factor

$$I_0 = \frac{I \cdot E_0 \cdot C}{M \cdot I_r}$$

Corrected I-V at 25 °C

$$V_0 = V - R_s(I_0 - I)$$



The light intensity may change slightly during the course of I-V measurements

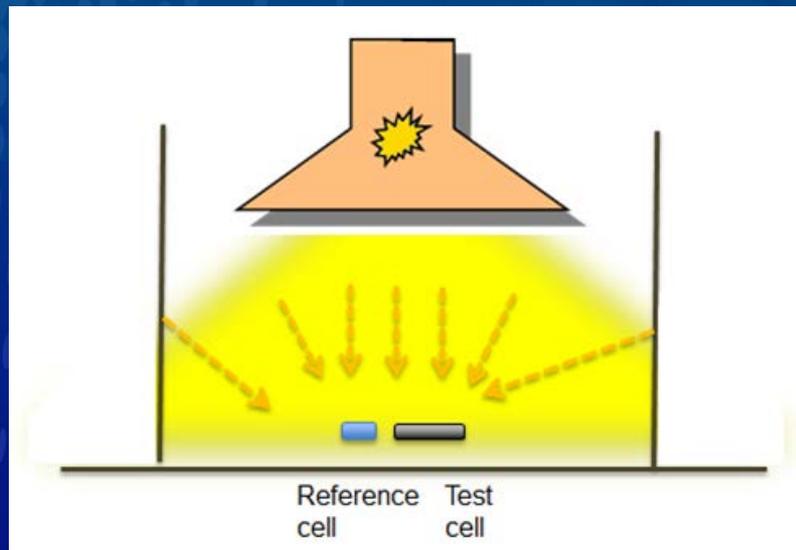


Directional Response

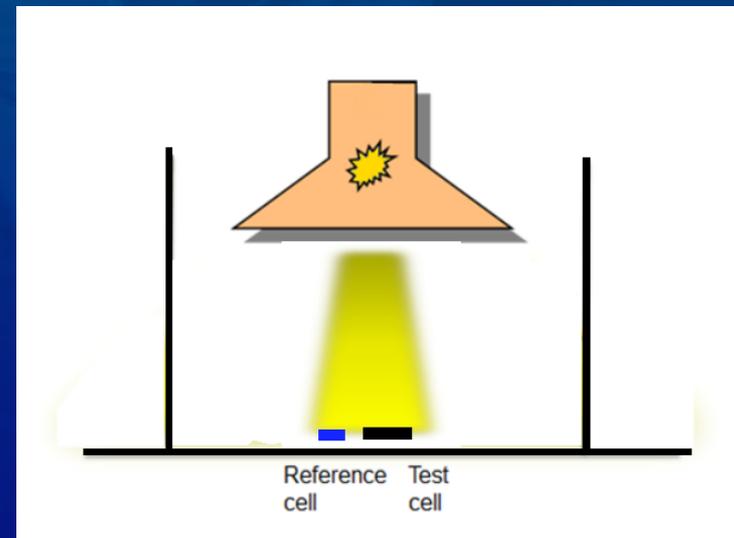
Assuming that the solar simulator is well characterized, i.e., AAA class, the differences in the directional (angular) response of the test and the reference cell can introduce errors

When does this become an issue?

Mostly diffuse source



Collimated source



The discrepancy arises because reference cells are (supposed to be) calibrated under mostly direct lighting conditions (AM 1.5 G: 88 % direct, 2 % circumsolar, 10 % diffuse)
Remedy: Characterize the cosine response of both Ref. and Test cell, use less diffuse, more normal incident light sources.



Summary and acknowledgement

- Mismatch-corrected AM 1.5 traceable I-V measurements.
- EQE/Spectral response measurements both in power mode and irradiance mode
- Spectroradiometric measurements and calibrations.
- Cell nonlinearity measurements
- Not discussed here: outdoor characterization and measurement of installed systems



- AC Measurements
- DC Measurements at the Circuit or String (residential only) Level
- Backside temperature measurements on a few modules
- Local solar irradiance and wind speed/direction measurements
- Data sampling rates of 1 and 10 second
- Automated cameras (effects of clouds, near shading, snow)

Special thanks to John Roller, Brian Dougherty, Matthew Boyd and Howard Yoon

