July 1998 ● NREL/CP-530-23878

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Presented at the 2nd World Conference and Exhibition on
Photovoltaic Solar Energy Conversion; 6-10 July 1998; Vienna, Austria

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1617 Cole Boulevard
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A national laboratory of the
U.S. Department of Energy
Managed by the Midwest Research Institute
For the U.S. Department of Energy
Under Contract No. DE-AC36-83CH10093

PHOTOVOLTAIC SPECTRAL RESPONSIVITY MEASUREMENTS

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ABSTRACT: This paper discusses the various elemental random and nonrandom error sources in typical spectral responsivity measurement systems. We focus specifically on the filter and grating monochrometer-based spectral responsivity measurement systems used by the Photovoltaic (PV) performance characterization team at NREL. A variety of subtle measurement errors can occur that arise from a finite photo-current response time, bandwidth of the monochromatic light, waveform of the monochromatic light, and spatial uniformity of the monochromatic and bias lights; the errors depend on the light source, PV technology, and measurement system. The quantum efficiency can be a function of the voltage bias, light bias level, and, for some structures, the spectral content of the bias light or location on the PV device. This paper compares the advantages and problems associated with semiconductor-detector-based calibrations and pyroelectric-detector-based calibrations. Different current-to-voltage conversion and ac photo-current detection strategies employed at NREL are compared and contrasted.
Keywords: Experimental Methods - 1: Calibration - 2: Performance - 3

1. INTRODUCTION

The spectral responsivity or quantum efficiency (QE) is essential for understanding current generation, recombination, and diffusion mechanisms in photovoltaic devices. PV cell and module calibrations often require a spectral correction factor that uses the QE. The quantum efficiency in units of electron - hole pairs collected per incident photon is computed from the measured spectral responsivity in units of amps per watt as a function of wavelength.

Typically, the spectral response is measured at short-circuit current. The measured photo-current is often in the μA to mA range with a broadband DC bias light near the devices intended operating point e.g. 1-sun. PV devices normally operate near their maximum power point, This is not normally a problem except in the case of amorphous silicon where the QE is voltage dependant.

The elemental error sources in the determination of the spectral response can be separated into errors in measuring the photo-current and errors in measuring the incident light power. Table I lists error sources in measuring the photo-current for a generic spectral response system. Formal and informal intercomparisons between measurement laboratories have shown significant differences in the relative spectral responsivity because of calibration errors, bias light dependence, light source emission lines, and other unknown sources [1-4]. ASTM Standard E1021 estimates a 0.3% repeatability and 1.7% reproducibility limit in the spectral mismatch parameter calculated using the spectral response data measured by the various participants in an intercomparison [5]. The final reports of the PEP'87 and PEP'93 international intercomparisons show graphically significant wavelength-dependent differences [6,7]. Understanding the various possible random and nonrandom error sources for a given system and minimizing the dominant error sources is essential to reliable absolute or relative quantum-efficiency measurements.

2. NREL MEASUREMENT SYSTEMS

A variety of spectral response measurement systems have been designed by the PV community, including systems based on interference filters, grating monochrometers, and interferometers [2-4,6-8]. Spectral responsivity measurements have been performed by the PV Cell and Module Performance Characterization team at NREL since 1983 on the filter-monochrometer-based system shown in Fig. 1 [3,9]. The system originally used stepping solenoids controlled by digital logic. Modifications are currently underway for a fourth filter wheel and real-time calibrations. An operational amplifier rated at ±40 V, 8 A is used as a current-to-voltage converter with a computer controlled gain of 50 to 10,000. Insertion of a power supply in series with the PV device allows bias voltages up to ±40 V. When an ac amplifier with a gain of 1, 10 or 100 is used the ac signal is typically in the 0.3 to 3 V range, allowing the ac signal to be measured with an ac voltmeter instead of the more traditional lockin amplifier. Modern digital lockin amplifiers have rapid auto-ranging capabilities and will outperform an ac voltmeter for noisy signals. The use of the shutter is essential for the ac voltmeter, but is less important when using a lockin amplifier. The monochromatic beam power is measured with a Laser Probe model 5710 radiometer with a RKP 575 pyroelectric head and a calibrated Si detector.

The grating system shown in Fig. 2 was developed to measure the responsivity of thermophotovoltaic cells from 400 to 2800 nm. This system uses a Laser Probe 5900 elec-

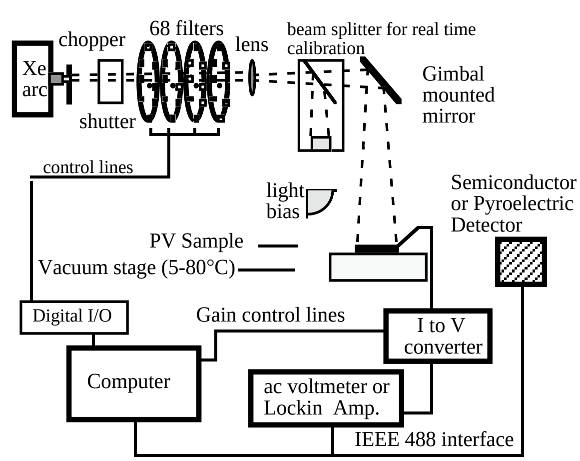

Figure 1: NREL filter QE system with a 280-2000 nm wavelength range.

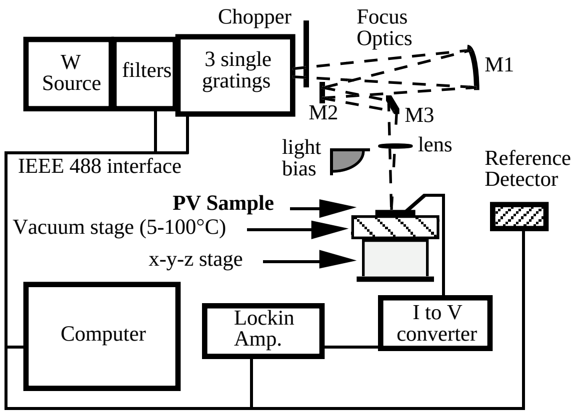

Figure 2: NREL grating monochrometer QE system

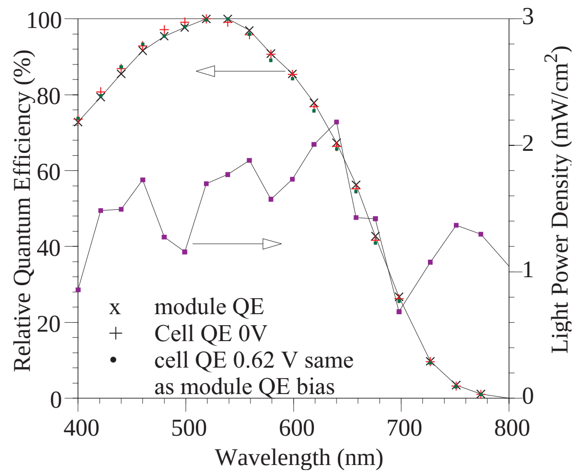

Figure 3: Module *vs.* cell QE measured with the filter system on a Solarex SA5 module.

trically calibrated pyroelectric radiometer (RSP-590/RSV head). Si detectors calibrated by the National Institute of Standards and Technology are also used for calibrations with estimated uncertainties of 0.2% to 2% from 400 to 1150 nm and higher elsewhere [10]. Semiconductor-based calibrations are useful where the photocurrent is known within a multiplicative constant. If the same amplifier is used to measure the reference and unknown PV devices, then uncertainties in the gain drop out. For semiconductor calibrations, the chopper phase is irrelevant, whereas the Laser Precision 5900 pyroelectric radiometer requires that the chopper be manually adjusted until the phase is correct. Semiconductor-based calibrations allow the test and reference signals to be filtered independently to maximize the signal-to-noise ratio.

3. PROCEDURES FOR MODULE QE

It is often desirable to measure the QE of modules consisting of multiple cells in series. The simplest approach would be to illuminate the whole module with ac monochromatic and dc broadband light with the module at 0 V, just as in the case of cells. The NREL filter system shown in Figure 2 is capable of fully illuminating any commercial module. This approach gives reasonable data sometimes. The problem with this method is that different cells may be current limiting at various wavelengths, and the bias point of the current-limiting cell whose QE is being measured is not at 0 V. This problem is similar to the multijunction amorphous silicon QE measurement problem addressed by Burdick and coworkers [11]. The solution to the problem for modules is to:

1. bias the module with light to simulate “1-sun.”

2a. forward bias the module to the measured open-circuit voltage (V_{oc}) times (n-1)/n, where n is the number of cells in series.

2b. Another procedure is to set the monochrometer to a wavelength that the cell responds to and to reduce the forward bias voltage from the measured V_{oc} towards 0 V until the ac signal is a maximum.

3. shine the monochromatic light on only one cell.

4. reduce the bias light on the cell that sees the monochromatic light in regions where there is no monochromatic light to ensure that this cell is current limiting.

The region where the monochromatic light strikes the sample does not need light bias if the QE is linear. A custom fixture was made for thin film modules that restricts the beam on the NREL filter system to illuminate just one narrow rectangular cell. Figure 3 shows an example of a module QE measurement on a Solarex SA5 amorphous silicon module where the individual cells have also been contacted. If all the cells in the module were identical, then the bias measured would be 0 V using the method given in step 2a and not 0.62 V. The advantage of method 2b is that the QE is maximized. The light bias level was 3-7% of one-sun as measured with a filtered silicon reference cell depending on where the light was measured. Figure 3 also shows the monochromatic light power density for the approximate 10 cm diameter beam produced by the filter QE system shown in Fig. 1. The monochromatic power density can be increased by focusing the beam to a smaller spot.

4. QE MEASUREMENT ERROR SOURCES

Spectral responsivity measurements involve the measurement of the photo-current produced by light of a given wavelength and power. The quantum efficiency is typically measured with bias light simulating reference conditions, because the device may be nonlinear [1-7]. Typically, the spectral correction factor for efficiency measurements is calculated based on QE measurements near 0 V and is assumed to be the same as at the maximum power point. This assumption is valid for most PV systems and results in a negligible error for amorphous silicon, which has a voltage-dependent spectral responsivity [12].

Error sources related to the measurement of the photocurrent are summarized in Table I. If semiconductor-based calibrations are employed with the same electronics used to measure the test and reference device, then all multiplicative errors drop out. For pyroelectric-radiometer-based calibrations, the absolute photo-current must be measured for absolute QE measurements. Commercial I-to-V converters typically have a limited maximum current of around 10 mA. This limitation is removed for I-to-V converters based on operational amplifiers.

For absolute current measurements, the measured lockin signal must be multiplied by a waveform correction factor that relates the measured RMS signal with the peak signal. This factor is $\sqrt{2}/2$ for a sine wave, $2\sqrt{2}/\pi$ for a square wave, and $2\sqrt{2}\cdot a\cdot \sin(\pi/a)/\pi^2$ for a trapezoid, with the constant π/a

Table I: Error sources for measurement of the photo-current.

- Electrical Instrumentation
  - current-to-voltage (I to V) converter
    - commercial current or custom amplifier
      - gain, linearity, noise, offset
    - shunt resistor
      - calibration, drift, thermovoltages
  - signal from I to V converter measured with
    - lockin amplifier (typically < 1 mA)
      - calibration, resolution, accuracy,
      - waveform to sine wave correction factor,
      - overloading, noise, dynamic range,
      - time-constant,
      - procedures for using lockin amplifier
    - an ac voltmeter
      - gain, offset from noise level,
      - linearity, time-constant
- PV cell or module
  - temperature,
  - response-time to periodic light,
  - linearity of PV device
  - white-light bias spatial uniformity,
  - monochromatic light spatial uniformity,
  - voltage bias of cell being measured,
  - spectral content of bias light,
  - device sensitivity to polarization of light
- Mechanical
  - mechanical movement of optics,
  - mechanical vibration,
  - chopped stray monochromatic light

Table II: Error sources for measurement of the light power.

- Filament or Xe-arc light source
  - intensity fluctuations,
  - change in spectral irradiance with age and current
- Real-time calibration
  - source-light polarization with a
    - glass beam splitter,
  - signal to noise,
  - detector characteristics,
  - calibration drift with time of monitor detector
- Stored calibration file
  - monochromatic source calibration drift with time
- Stray light
  - detector sees light that cell does not see,
  - area of detector different from device area,
  - different field of views,
  - monochrometer
    - incomplete attenuation of grating orders
  - narrow bandwidth filters
    - pinholes in the filter,
    - degradation of blocking filter,
    - insufficient blocking (~10^{-4})
- Reference detectors and associated electronics in general
  - calibration, resolution, accuracy,
  - gain, phase, offset, linearity,
  - spatial uniformity of detector element,
  - temperature drift,
  - change in the detector's field of view,
  - degradation of detector,
  - spectral response of detector
- Pyroelectric detector
  - different instrumentation used to measure cell and reference
  - time constant of detector,
  - microphonics, signal to noise,
  - phase-angle adjustment,
  - waveform factor (square wave assumed)

being the radian angle at the top of the rising edge of the trapezoidal waveform [13].

The response time of PV devices to chopped light can be a problem for electrochemical cells. Similar to results reported elsewhere, chopping frequencies below 4 Hz are required to keep the waveform from changing with frequency [14]. This effect is more pronounced at low light levels and in the infrared.

It is important that light from the bias light source not be allowed to go through the light chopper. A simple procedure to determine if the sample is seeing chopped stray light is to turn off the monochromatic light source and measure the test device's response as a function of bias light intensity.

A variety of error sources associated with measuring the monochromatic light power are listed in Table II. The measurement of the monochromatic light power can be performed with radiometric detectors or semiconductor detectors. When a quartz slide is used as the beam splitter, then errors in the power can arise because of polarization effects. The light off the monochrometer is polarized, and the polarization angle can change with a grating change. The bandgap, photoluminescence, and absorption coefficient for PV devices can be sensitive to the polarization angle. The light reflected off a glass surface will have a different polarization than the light reaching the test plane and will be of much lower intensity. These effects are minimized if a calibration is performed with the detector in the test plane and the file stored to disk. This procedure is required at least once for real-time calibrations. Real-time calibrations account for the change in spectrum with lamp age, current, and time among other things.

If the beam is larger than the sample, then the spatial uniformity of the monochromatic beam is important. For the NREL filter monochrometer system, spatial nonuniformities of ±10% are typical and, more importantly these errors can change with wavelength because of variations in the transmission of the filter and spatial variation in the output of the Xe-arc lamp. Electrically calibrated pyroelectric detectors are spectrally flat from the ultraviolet to far infrared and have a low broadband error of less than ±2%, but are sensitive to microphonics, temperature changes within the detectors field of view, and have noise at the 0.01 µW cm^{-2} level. Semiconductor-based detectors are not sensitive to light outside their relatively narrow response range and can be measured with the same electronics used to measure the test device, eliminating any wavelength-independent multiplicative error sources. Semiconductor-based detectors can drift with age [15] and have temperature coefficients exceeding 1 %/°C near their bandgap. Figure 4 shows the quantum efficiency of a cell measured with a pyroelectric based detector and semiconductor based detector. The light power of the grating monochrometer based system is focussed to a rectangular spot approximately 1 by 3 mm. The monochro-

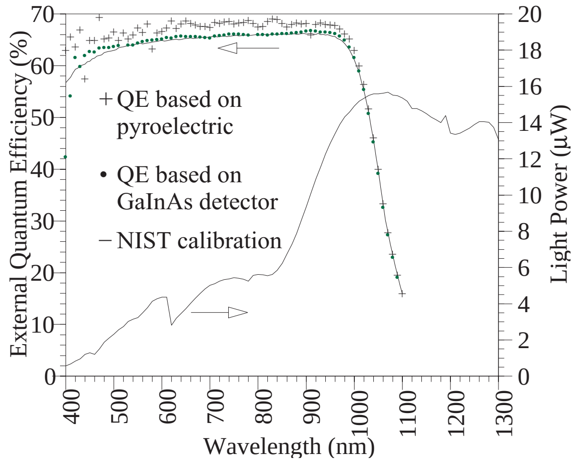

Figure 4: Comparison of semiconductor and pyroelectric based QE measurements on a NIST calibrated Si detector with the NIST calibration.

matic light power for the filter QE system (Fig. 3) is approximately 20,000 times greater than for the grating system (Fig. 4). The random error in the measured QE's in Fig. 4 are summarized in Table III. The Laser Probe 5900 electrically calibrated pyroelectric radiometer in Fig. 2 has a total error of ±0.9% for a 3 mm beam and 95% confidence. Table IV summarizes the error in the QE that can occur because of the monochromatic light. Many of the error sources listed in Tables II and IV are discussed in detail by Kostkowski [16]. The bandwidth of the monochromatic light can contribute to the error near the band gap or when the light transmitted through a bandpass filter is highly asymmetric [13]. These errors have a small effect on the spectral correction factor when the bandwidth is less than 10 nm [13].

5. CONCLUSIONS

A method has been presented to measure the quantum efficiency of modules that is consistent with accepted procedures for measuring the quantum-efficiency of multijunction cells. Various sources of uncertainty for quantum efficiency measurement systems are discussed. Absolute quantum-efficiency measurements with a total uncertainty of less than ±2% are possible, but only with extreme measures to minimize all error sources [3,6].

Table III: Errors in Grating QE Measurements at NREL

Uncertainties	Pyroelectric Calibration File[1,2]	NIST calibrated QE of D205[3]	QE of D205 based on GaInAs Calibration[2]
400-500 nm	15.0%	1.56%	4.0%
500-600 nm	10.0%	0.24%	0.5%
600-900 nm	4.5%	0.24%	0.5%
900-100 nm	3.0%	4.00%	0.5%

[1]Data not available for pyroelectric calibrated QE
[2]Random error, 95% confidence
[3]Relative expanded uncertainty (k=2) extracted from NIST calibration

Table IV: Error sources related to the monochromatic light.

Bandwidth,
Filter defects,
Polarization variation with wavelength,
Wavelength offset,
Wavelength variation with temperature,
Beam wanders with wavelength,
Beam larger than the test device
- detector area versus PV area,
- position of detector and PV different,
- spatial uniformity of beam

Beam smaller than detector and device area
- partially shaded regions,
- spatial variation in responsivity of PV

6. ACKNOWLEDGMENTS

This work is performed under Contract No. DE-AC36-83CH10093 to the U.S. Department of Energy.

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