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A NEW REAL-TIME QUANTUM EFFICIENCY MEASUREMENT SYSTEM

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ABSTRACT

We have developed a new technique for measuring the quantum efficiency (QE) in solar cells in real-time using a unique, electronically controlled, full-spectrum light source. Full-spectrum QE graphs can be obtained in less than one second (as opposed to 20 minutes using traditional QE instruments). The high measurement speed is achieved by parallel processing of information from a multitude of spectral channels encoded in modulation frequency bands. The reduction in time scale makes this QE measurement technique compatible with inline production diagnostics, high-fidelity, spectral-matching cell binning, and thin-film module spatial spectral response uniformity tests. The instrument is completely solid-state with no moving parts, is robust enough for manufacturing environments, and is significantly less expensive than a traditional QE instrument.

INTRODUCTION

Quantum efficiency (QE) or spectral response measurements are extremely valuable tools for understanding device physics and materials properties of solar cells. A QE diagram can reveal material band gaps and thicknesses in single and multilayer solar cells, minority carrier diffusion lengths[1], spectral-dependence of short circuit current and qualitative spatial electronic behavior within cells[1,2]. Traditionally, QE measurements are made with a mechanically driven spectrometer to direct monochromatic, chopped light onto a cell. Lock-in amplifier techniques measure the cell response (collected electron-hole pairs/photon flux) in a serial manner over the spectrum of interest. To obtain good signal-to-noise in the data and to allow time for mechanical switching of wavelengths within the monochromator, measurements typically take 20 minutes (after system calibration). Because of this time burden, QE instruments are typically only found in laboratory settings – never on cell production lines.

This paper discusses the development of a new technique for measuring the quantum efficiency in solar cells that reduces the time for measurement from 20 minutes to less than one second. This time reduction makes QE measurements compatible with cell and module production-line speeds, bringing a higher level of diagnostics to solar cell and module manufacturing. We envisage making the new QE system available for in-line cell diagnostics, high fidelity, spectral-matching cell binning, and thin-film module spectral response uniformity tests across the solar cell and module industry.

The new real-time quantum efficiency (RTQE) system, developed at NREL, shifts a QE measurement from serial to parallel, thus taking the entire QE spectrum simultaneously in less than one second. It is similar in nature to the instrument by Bucher and Schonecker[3]; however our approach is less complex, considerably less expensive, completely solid state and significantly faster.

PRINCIPLE OF OPERATION

The high measurement speed is achieved by parallel processing of information from a multitude of spectral channels encoded in modulation frequency bands. This is achieved by an electronically controlled, full-spectrum light source (ECLS) that allows individual on/off frequency control over specified spectral ranges. The ECLS is an electronically controlled array of light emitting diodes (LED), each with a unique spectral emission, but with a slight overlap in wavelengths such that the ECLS spectrum covers a typical solar cell spectral response (300 nm – 1200 nm). Figure 1 shows the individual LED spectra for one embodiment of the ECLS which uses 57 LEDs. A sine-wave generator and an amplifier, both of which are controlled by a computer, power each LED in the ECLS. This arrangement allows for each LED to operate at a unique frequency and/or intensity. Light from the LEDs in the ECLS is focused to a common area either by lenses, mirrors or by fiber optics.

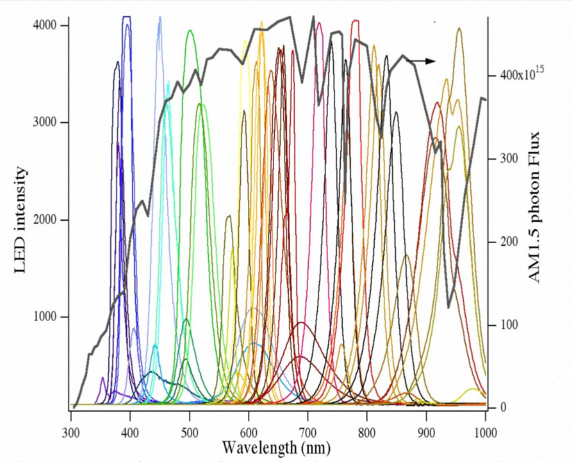

Figure 1. (left axis) Spectra of the individual LEDs in the electronically controlled light source using 58 LEDs. (Right axis) AM1.5 solar spectrum.

A schematic of the ECLS and the RTQE system is shown in Figure 2.

The RTQE system works by focusing light from the

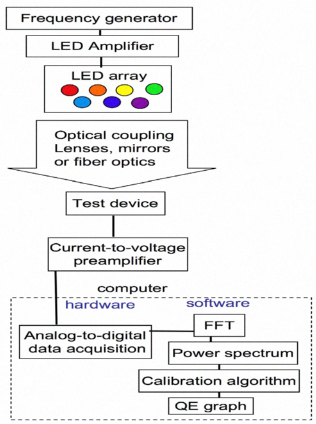

Figure 2. Schematic of the real time quantum efficiency instrument.

ECLS onto a solar cell with each LED in the ECLS switched on and off at a unique, specified drive frequency. All of the LEDs in the array are driven simultaneously. The drive frequency of each LED is set below the inverse response time of the cell and is not a multiple of the other LED drive frequencies. The response of the cell or the A.C. current vs time signal (Figure 3) is sent through a current-to-voltage preamplifier after which it is recorded by a computer-based analog-to-digital converter (DAQ card). The digitized signal is then Fourier transformed to determine the power spectrum (Figure 3). The power spectrum separates out the frequency components of the total signal that exactly match the specified drive frequencies of the LEDs in the ECLS. The amplitude of the power spectrum frequency components are directly related to the current generated in the cell from the light of the corresponding LED. Calibration of the system is done with a reference cell by scaling the known current to the amplitude of each frequency component in the power spectrum. A computer program continuously records the data, applies the calibration algorithm, and updates a QE graph. A QE graph is obtained by assigning the current generated for each drive frequency to the peak wavelength of the associated LED. The update rate of the QE graph is determined by the capture rate of the analog-to-digital converter and by the integration time of the power spectrum. Typical graphical update rates are less than 1 second. Figure 4 shows a QE graph measured by the RTQE system (dots) using a prototype 10-LED ECLS. The dashed line in fig. 4 is the QE measured by a traditional QE system. The agreement between the techniques is excellent.

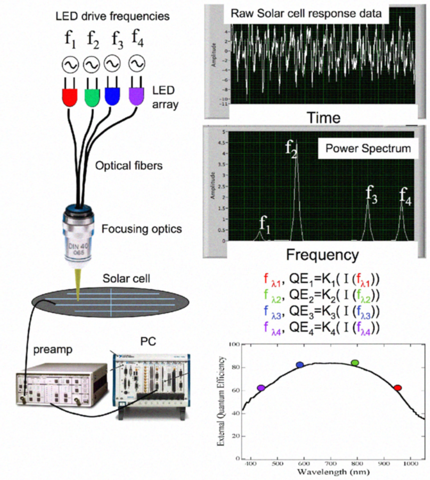

Figure 3. Schematic of an RTQE system and data using a 4-LED ECLS. All of the LEDs flash simultaneously at a unique drive frequency (f1, f2, f3, f4) onto the solar cell. The current from the solar cell is converted to voltage and read by a DAQ card in the PC. Next, the raw voltage vs time data are transformed into a power spectrum using FFT mathematics. The power spectrum separates out the current contributions from each LED by mapping the drive frequencies of each LED to the corresponding peak(f) in the power spectrum. Calibration constants (K1-K4), determined with a reference cell, convert the amplitude of the power spectrum peaks to QE values. A QE graph is constructed from the peak wavelengths of the LEDs and the calibrated QE values.

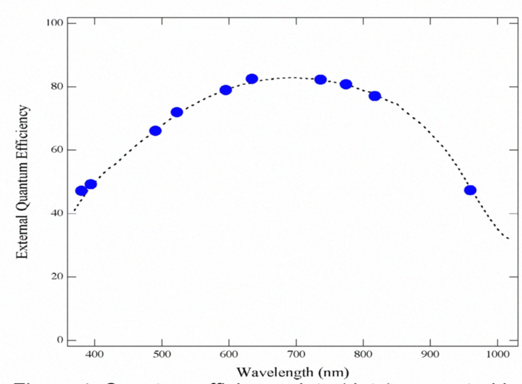

Figure 4. Quantum efficiency data (dots) generated in <1 second using a 10-LED prototype RTQE system. The dashed line is QE data from a traditional QE system.

TECHNICAL NOTES

The RTQE system is a very fast and stable technique for measuring the quantum efficiency in solar cells. To implement the new method, however, several technical considerations should be addressed.

1) Selection of LEDs: An enabling technology for the RTQE system has been the tremendous progress in available LED spectra and intensity. When choosing LEDs for the ECLS one should consider spectral symmetry and intensity. Some LEDs appear to the human

eye to have a single color but in fact are a combination of two or more colors mixed together. LEDs with a true single color (spectral symmetry) simplify the calibration (see #4) and interpretation of the power spectrum and should be used in the ECLS whenever possible. If some LEDs are not intense enough to produce good signal to noise, multiple, identical LEDs can be ganged together.

2) LED drive signal: To produce a noise-free, single peak in the power spectrum, the response of the solar cell from each LED should be sinusoidal. Due to non-linearity in LEDs and solar cells, the drive voltage for each LED should be considered. Applying an offset D.C. voltage with a superimposed "dither" voltage has proven successful in our prototypes.

3) Drive frequency: As mentioned above, the drive frequency for each LED should be carefully chosen. In general, the drive frequencies for each LED should be selected such that there is no overlap in power spectrum peaks. Practically this means drive frequencies should not be multiples of each other and should be shifted away from large secondary harmonic peaks in the power spectrum due to non-sinusoidal current response in a solar cell. Drive frequencies should be high enough to allow fast data averaging, but low enough to allow electron hole pairs time to be collected.

4) LED spectral spread: Because light emission from LEDs is not monochromatic[4], there is a spectral spread in wavelength on the order of 10 - 40 nm over the response spectrum of C-Si, inherent with each data point in the QE graph. The wavelength resolution of the QE graph by this technique is determined by the spectral spread of the individual LEDs and by the number of different-spectrum LEDs in the ECLS. The spectral spread of the individual LEDs and the spectral overlap between LEDs can be accounted for in a calibration algorithm that utilizes Singular Value Decomposition (SVD) matrix algebra. Solid-state lasers could also be used instead of LEDs in the ECLS to give sharp spectral bandwidths.

5) Data Acquisition: Data acquisition rates should be at least twice the highest drive frequency in the ECLS to avoid aliasing.

Expanded Applications

The RTQE instrument is completely solid-state with no moving parts, is robust enough for manufacturing environments, and is significantly less expensive than a traditional QE instrument. Except for the highest resolution QE measurements ($\Delta\lambda$ ~ 1-2 nm) the RTQE (with LEDs in the ECLS) could replace traditional QE measurement systems in the laboratory saving time and money. Additionally, the speed of the RTQE instrument allows QE measurements to be made on every cell and module in a manufacturing line during standard contacting for current versus voltage tests. The ability to measure QE on each cell could allow for finer binning of cells by spectral-matching "identical" short-circuit current cells. This finer binning of cells would account for daily and yearly AM1.5 solar spectral shifts, which could maximize annual KW*hr output from a module. Additionally, the RTQE system allows new production-line materials diagnostics and device physics feedback not available in current production lines.

Spatial spectral-response uniformity mapping at the cell and module (thin-film modules) level is now practical with the RTQE system. Either serial (single RTQE) scanning or parallel (multiple RTQE units) mapping could be utilized.

QE measurements of multijunction solar cells can be made with the RTQE system through electronic control of the spectrum (electronic filtering) from the ECLS to light bias different sub-cells within a monolithic tandem cell. Electronic filtering is achieved by dividing the ECLS LED array into sub-cell-specific spectra so that the sub-cell under test is illuminated with drive-frequency light, while the other sub-cell specific spectra are driven by a constant DC bias. This electronic filtering allows only the sub-cell under test to be measured (only the drive frequency spectra produce a QE power spectrum), while all the other sub-cells are DC light biased to proved carrier transport to the contacts.

A follow-on to the electronic filtering idea is to match a specific spectrum with the ECLS by varying the intensity of the individual LEDs in the array. Almost any spectra of choice (AM0, AM1.5, Moon, Mars, etc.) can be quickly and easily simulated.

NREL has developed prototypes of the system and has secured licensable intellectual property rights. We are seeking industrial partners to commercialize this technology to the solar industry. Interested parties should contact the Technology Transfer Department at NREL, (David Christensen, david_christensen@nrel.gov, +1 (303) 275-3015). Technical questions can be addressed to david_young@nrel.gov.

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