# Electroluminescence Excitation Spectroscopy: A Novel Approach to Non-Contact Quantum Efficiency Measurements

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*Abstract* — **In this work, we introduce electroluminescence excitation spectroscopy (ELE) as a non-contact proxy for extracting the quantum efficiency (QE) of a photovoltaic (PV) cell. This method differs from photoluminescence excitation (PLE) by physically separating the absorbing and emitting regions of the cell. It eliminates the influence of voltage independent carriers and solves the challenge of separating the reflected signal from the emitter signal at long wavelengths. Here, the spectrally resolved AC optical excitation drives current to the detection area in a manner similar to non-contact EL. The strength of the EL signal is dependent on the amount of current generated by the spectrally resolved AC optical excitation. Additionally, a separately controllable DC light bias is introduced to control the overall bias state of the cell under test.**

## I. Introduction

Quantum efficiency (QE) measurements provide a critical tool to assess the quality of photovoltaic (PV) cells. Traditionally, this technique involves illuminating a small area of the cell with monochromatic light of a known irradiance ($G$) and measuring the short-circuit current density ($J_{SC}$) from the cell. The spectral response is obtained by calculating ($J_{SC}/G$) as a function of incident wavelength ($\lambda$) and then translating that into QE, the percentage of incident photons that generate a collected carrier. Electrical contact to the cell is required since a $J_{SC}$ measurement is required. The requirement to scan through different wavelengths for each $J_{SC}(\lambda)$ measurement means QE measurements traditionally take a long time, on the order of minutes, making them incompatible with in-line metrology. However, recent developments have cut QE measurement times substantially, as low as one second [1]. For example, the FlashQE approach uses an array of 64 light emitting diodes (LEDs) with different wavelengths, where the intensity of each is modulated under closed-loop control at a unique AC frequency [2]. The LED output is combined into a single beam that illuminates the cell, and a Fourier transform is performed on the time-resolved $J_{SC}$ of the cell to decouple the contribution from each wavelength. This development opens the door for in-line QE measurements, but it is inherently a contacting technique, and so can only be used at the point of conventional cell test and sort.

The ability to perform a one second non-contact QE measurement is attractive for a number of reasons. A technique that uses only photons in and photons out eliminates wafer breakage that results from contacting the cell, and does not require maintenance or replacement of pogo pins. It may also be used in various geometries (e.g., linescan of moving cell, full area average of motionless cell, small spot measurement at the center of cell). Additionally, implied QE measurements of unmetallized wafers can also be performed, meaning the technique could potentially be used upstream in manufacturing.

Spectrally resolved photoconductance and photoluminescence excitation (PLE) have been used to obtain non-contact QE curves [3], but both have weaknesses. Photoconductance can't be performed on finished cells, but only on unmetallized wafers. For cells made of indirect bandgap materials, the long wavelength response of both photoconductance and PLE is heavily influenced by voltage independent carriers [4]: in silicon this limits their use to wavelengths less than 950 nm. Additionally, PLE measurements near the bandgap of the material are confounded by the difficulty of distinguishing the luminescence signal from the incident light. For silicon process control of modern cells, this long wavelength regime is particularly important, as it is sensitive to the passivation and reflectance of the back surface.

In this work, we introduce a novel non-contact QE measurement technique based on electroluminescence excitation (ELE). This approach physically separates the absorbing and emitting regions of the cell to eliminate the influence of voltage independent carriers and the challenge of separating the reflected signal from the emitter signal at long wavelengths. In addition, a separately controllable DC pump beam is introduced to control the overall bias state of the cell under test. Both the first and second generation designs of the system are shown in Figure 1.

Here, the spectrally resolved AC optical excitation drives current to the detection area in a manner similar to non-contact EL [5-7]. The strength of the EL signal is dependent on the amount of current generated by the AC optical excitation. The detector synchronously locks into the frequency of the AC optical excitation to separate this signal from the DC light bias and background light, significantly improving the signal to noise ratio.

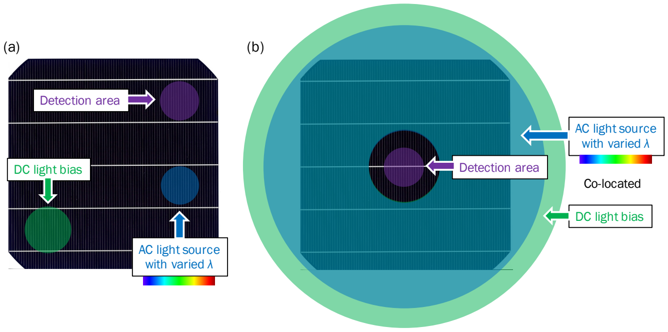


Figure 1. Illustration of the illumination sources and detection area for non-contact QE system used in this work, including: (a) the first generation design; and (b) the second generation design.

## II. MODELING APPROACH

Lateral balancing currents are a fundamental part of this measurement, supplying the current to the detection area, analogous to a non-contact EL measurement. The role of lateral balancing currents is investigated using circuit simulations with LTSpice. In this case, a simple equivalent circuit is used with three separate elements connected in parallel (Figure 2): (Region 1) the DC light bias is modeled as a one-diode cell with large photogenerated current density ($J_G$); (Region 2) the spectrally resolved AC light source is modeled as a one-diode cell with a smaller $J_G$, this is the region under test; and (Region 3) represented by a one-diode cell with no $J_G$ source: this region generates the detected EL signal.

Region 3 may be imagined as an external LED connected in parallel with the region under test. The region under test supplies current to this external LED, and the emitted intensity acts as a proxy for QE. The EL emission strength is plotted vs. excitation wavelength to provide a full-spectrum measurement.

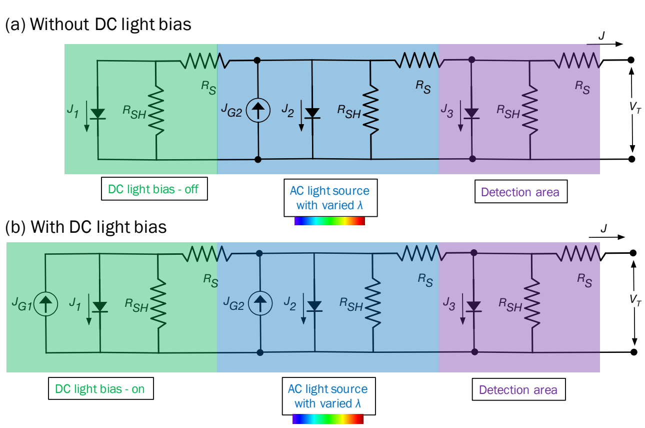


Figure 2. Equivalent circuit used in the LTSpice simulation for the configuration (a) without DC light bias and (b) with DC light bias.

## III. EXPERIMENTAL DETAILS

Both the first generation and second generation prototype systems used in this work are shown in Figure 3. For the first generation system, shown in Figure 3(a), the light emission from a set of AC modulated LEDs ($\lambda_1$, $\lambda_2$, …) is injected into an integrating sphere which contains a monitor photodiode to measure, in real time, the intensity of each wavelength. The exit port of the sphere is held in close proximity to the cell, illuminating Region 2, as defined earlier. A separate DC light bias is directed toward Region 1. This controls the overall forward bias of the cell, and therefore the gain of the emitting region. Region 3 is defined as the detection area, where the resultant EL signal is collected by a simple lens and photodetector.

Note that this 'ELE' arrangement solves several problems that have historically prevented the use of in-line PLE in silicon devices. (1) Incident photons are not present in the detection area, and so the technique is inherently full-spectrum (i.e., there is no need to reject incident photons from the detection area). (2) Incident photons do create 'voltage independent carriers' in Region 2, but these do not affect the emission from Region 3. This approach ensures that only voltage dependent carriers modulate the emission signal since the detection are is operating in an EL mode. This makes the technique significantly more useful in indirect materials.

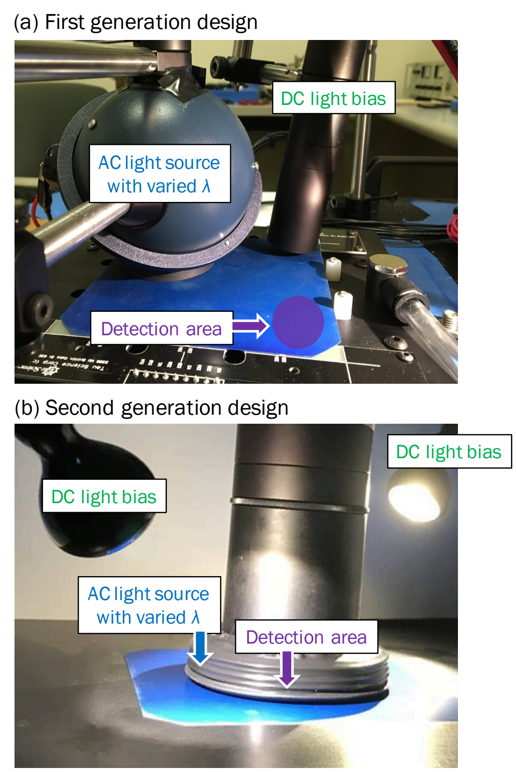


Figure 3. Experimental setup used to perform the ELE spectroscopy technique, including: (a) the first generation prototype; and (b) the second generation prototype.

The second generation design simplifies the measurement setup by featuring a single column that comes down near the cell, wherein the LEDs illuminate a ring around the detection area, seen in both Figure 1(b) and Figure 3(b). Additionally, inexpensive broadband DC light sources illuminate a larger area at the periphery of the column.

## IV. Results and Discussion

The circuit simulations reveal some interesting features of this technique. The current-voltage (*I-V*) curves of each circuit element and at the terminals are given for the case with no DC light bias in Figure 4(a) and with a DC light bias in Figure 4(b). Because this is a non-contact technique, the point of interest here is the open-circuit condition where the terminal voltage ($V_T$) is zero. For the case with no DC light bias, the spectrally resolved AC light is the only excitation source and supplies current to the detection area. Here, the AC light acts as a source, operating somewhere between $V_{MP}$ and $V_{OC}$, while the detection area acts as a sink.

With a DC light bias (1 sun) larger than the spectrally resolved AC light (0.1 suns), the DC light bias supplies current to both the region under test and to the detection area. This has benefit of increasing the emission and gain of the detection area by increasing the operating voltage locally. Although the region illuminated by spectrally resolved AC light is now a sink, the variations in the local *I-V* curve still act to increase and decrease the operating point of the detection area. By locking in to the AC frequency, the current contribution from this region can be separated from the DC light bias providing a proxy for QE.

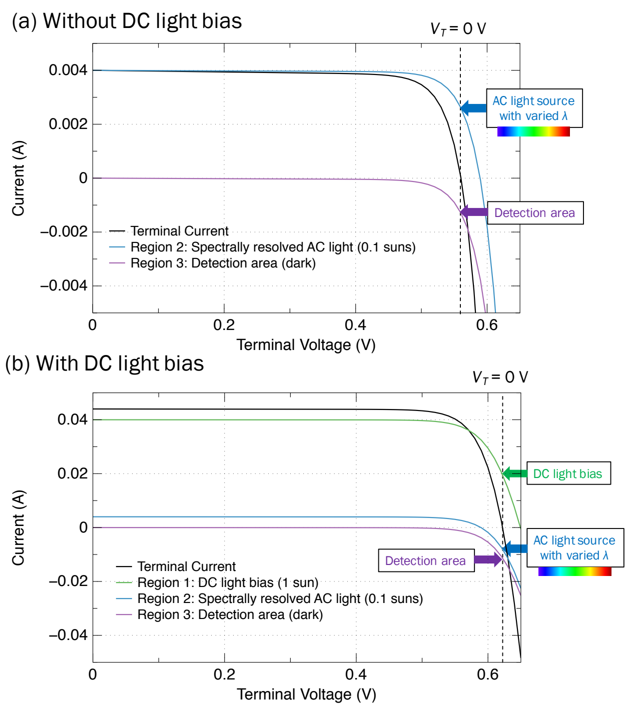


Figure 4. *I-V* curves of each circuit element and at the terminals for the case: (a) with no DC light bias; and (b) with a DC light bias.

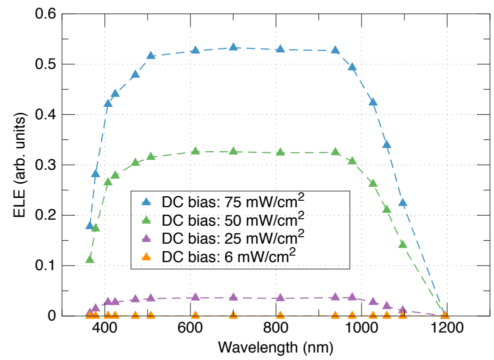


Figure 5. ELE measurements performed at different DC light bias levels with the first generation prototype system.

ELE measurements were performed on an industrial-scale monocrystalline silicon PV cell at different DC light bias levels using the first generation prototype system. The results are shown in Figure 5 and demonstrate the full-spectrum capability of the measurement system as well as the role of the DC light bias in increasing the signal strength.

EQE measurements with electrical contacts (using the FlashQE system described in [2]) and non-contact ELE measurements (second generation prototype) were both performed on two industrial-scale crystalline silicon PV cells, a multicrystalline silicon aluminum back surface field (Al-BSF) cell and a monocrystalline silicon passivated emitter and rear cell (PERC). The results are shown in Figure 6 and a comparison between the two shows rather good agreement. The team is still working to optimize the calibration procedure used to measure and adjust the flux from the individual LEDs.

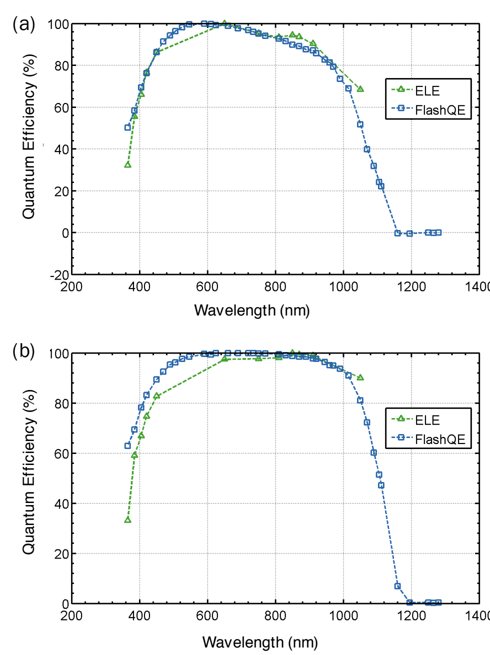


Figure 6. EQE (FlashQE) and ELE measurements (second generation prototype system) obtained on: (a) a multicrystalline silicon Al-BSF cell; and (b) a monocrystalline silicon PERC cell.

## V. Conclusion

Here, electroluminescence excitation (ELE) spectroscopy is introduced as a non-contact proxy for determining the quantum efficiency of a cell. Circuit simulation results demonstrate the role of the DC light bias in driving the lateral balancing currents that ultimately enable this technique to work. Experimental results comparing the external quantum efficiency measured with electrical contacts to the non-contact ELE measurements demonstrate good agreement for two different industrial-scale crystalline silicon photovoltaic cells. These results extend into the near infrared region of the spectrum and do not show any sign of voltage independent (i.e., diffusion-limited) carriers. Because the detection area operates in an EL mode, only voltage dependent carriers contribute to the emission signal detected.

## Acknowledgements

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