Nonlinear Response of Silicon Solar Cells

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***Abstract* — We used an LED-array-based combinatorial flux addition method to explore the wavelength and the intensity-dependence of the spectral responsivity in silicon solar cells. Many types of silicon cells, whether mono- or multi-crystalline type, exhibit notable nonlinear behavior of current with light intensity at illumination intensities below 0.01-sun equivalent levels. This effect is particularly pronounced when exposed to near-infrared light close to the peak of the spectral responsivity. However, some cases show the perseverance of nonlinearity all the way up to 1-sun intensity levels. In such cases, use of these cells as reference cells has implications for the accuracy of electrical performance measurements.**

I. INTRODUCTION

In an *ideal* photovoltaic (PV) solar cell, a linear relationship exists between the incident irradiance flux on the solar cell and the resultant photogenerated current output. Therefore, increasing the total irradiance by a factor of x should also result in a factor of x increase in the short circuit current (I_{sc}) of the PV device. However, most *real-world* PV devices do not follow this simple rule; rather, they show a nonlinear behavior that is both dependent on the spectrum of the incident radiation as well as the intensity of the illumination source itself. For most silicon solar cells that were evaluated in our laboratory, the nonlinear behavior described here appears at longer wavelengths (i.e., 600 nm to 1000 nm) and even then, it is generally revealed at very low intensities. However, there are unusual cases where a significant nonlinear behavior is observed even at incident intensities close to the standard reporting conditions (SRC), i.e., 1-sun equivalent intensities.

Traditionally, nonlinear behavior in solar cells and optical detectors have been evaluated by well-established methods such as the differential spectral responsivity (DSR) or AC-DC method [1], and the superposition method such as the two-lamp flux addition technique [2]. The DSR method can indeed be used to determine the actual mathematical relationship between the signal s (generally the I_{sc}) and the flux φ. However, the technique is time-consuming and the AC/DC current separation, especially at large ratios, presents a significant electrical engineering challenge. Also, the DSR method is usually implemented by use of a monochromator and it is difficult to change or modify the intensity of the monochromatic beam. Some superposition methods, such as the two-lamp method, based on comparing the ratio of the individually-added photocurrents obtained from two light sources to their combined two-source output, can reveal device nonlinearity, but do not provide any insight on the actual nonlinear relationship.

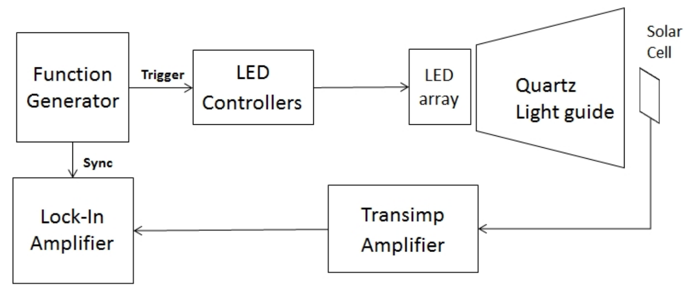

Fig. 1. Schematic of the nonlinearity measurement apparatus

In this work, we demonstrate the feasibility of using a combinatorial flux addition technique [3] based on the use of two sets of light emitting diode (LED) arrays to accurately measure the nonlinear behavior of a variety of silicon based solar cells, over a large range of signals (by controlling the intensities) and wavelength. Our results clearly indicate that linearity should not be automatically assumed when evaluating the performance of a solar cell under a given light intensity, or when using it as a reference cell for intensity measurements at conditions other than what it was originally calibrated or tested.

II. EXPERIMENTAL DETAILS

A schematic of the LED-based combinatorial approach is shown in Fig. 1. The measurement requires illumination of the cell by two *identical* LEDs (or sets of LEDs) in singular and a combinatorial fashion. To achieve this, commercial LED controllers with multiple independent current source channels were used to run each LED according to a prescribed schedule [4]. For each LED setting, the I_{sc} from the device under test (DUT) is recorded by way of a transimpedance preamplifier connected to a lock-in amplifier. All LEDs were operated

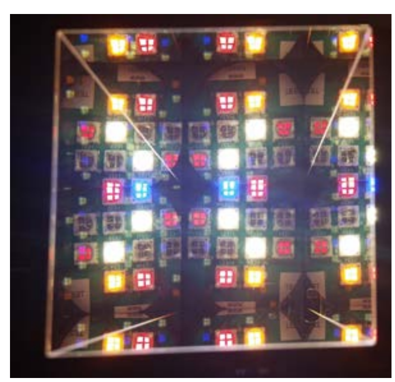

Fig. 2. The LED array as seen through the light guide

in pulsed mode through a trigger signal applied to the LED controllers by a function generator. Pulsing ensures better measurement stability and less drift in the LED signal during the course of the measurement. The light from the LEDs is coupled into a solid-glass, tapered light guide to ensure homogeneity and uniform illumination at the cell location. The nonuniformity for each LED at the cell location across the 50 mm exit port is up to 10 %. Fig. 2 shows an image of one such LED array as seen looking into the light guide from the front of the exit port. Both the circuit-mounted LED array and the light guide are custom designed and fabricated for our unique measurement needs.

For the data presented here, 15 unique current levels are sourced to LED 1 in a sequential way while the I_{sc} is recorded for each. This sequence is followed by 15 other current levels to LED 2 in a similar manner along with recording of the I_{sc}. Then combinations of these currents are applied to both LEDs simultaneously, usually in a manner whereby each current from source 1 is paired with 3 currents from source 2. Therefore, 45=15×3 combination fluxes are supplied and 45 signals are obtained from the cell. Thus, 75=15+15+45 total data points are measured in one run.

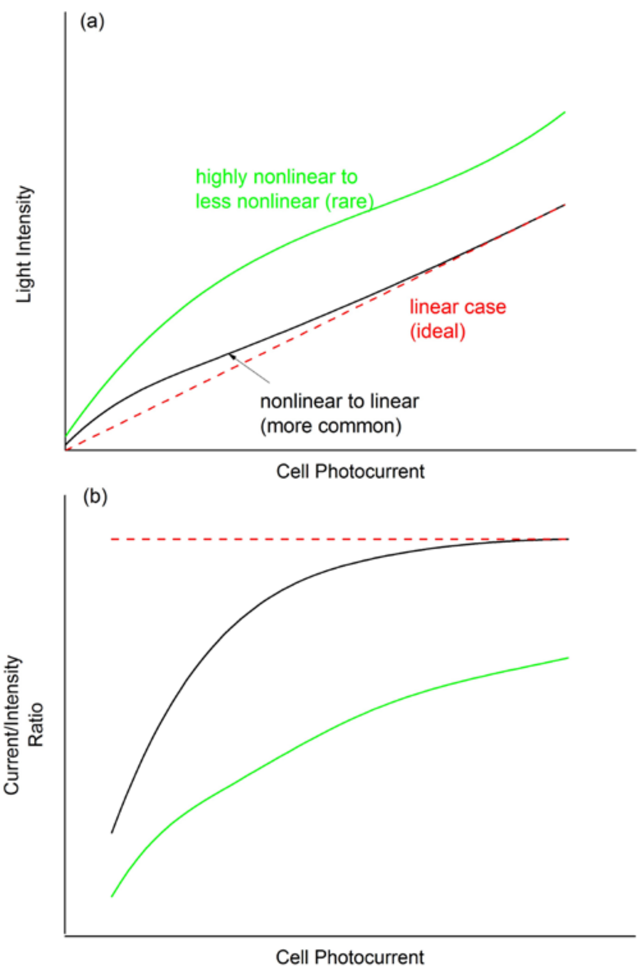

Fig. 3 (a) Two common forms of nonlinear behavior observed with Si cells (b) Representing nonlinearity with ratio plots.

III. Analysis and Results

A. Mathematical Framework

The objective is to use the combinatorial signal data to construct a linear system of equations relating signals and fluxes and solve for the unknown flux values and coefficients. This system of equations is overdetermined because the total number of unknowns is far smaller than the total number of equations (or signals). Assuming an Nth-degree polynomial model for flux ϕ (say, in W/m^2) as a function of short-circuit current signal s (say in A DC), i.e.,

$$\phi = r_0 + r_1 s + r_2 s^2 + \ldots + r_N s^N \quad , (1)$$

we can then write K equations for the K distinct fluxes from LED source 1, J equations for the J distinct fluxes from LED source 2, and M equations for the M combinations of the fluxes from both sources 1 and 2. As described in detail previously [4], these equations can be made *related* and solved by finding a linear least squares solution (or can be solved using a matrix-based approach) and the fluxes and the ratio of signal to flux values can be calculated for each signal value. Depending on the severity of the nonlinear behavior, it may become necessary to solve for the r_N coefficients up to N = 5 or more. The residuals of the fit determine the order, N. This solution remains unscaled. However, it is possible to obtain a scaled relationship if one or more calibrated flux values were known. Flux calibration can be achieved by using a reference photodetector with a known irradiance spectral responsivity. For most practical cases, it is sufficient to plot the ratio of signal to flux as a function of signal and observe whether it is constant or not. Constant cases correspond to a linear response whereas a changing ratio corresponds to a nonlinear behavior. It is noted that a signal to flux ratio is essentially an unscaled spectral responsivity.

B. Nonlinear vs Linear Behavior

Fig. 3 demonstrates the concept of nonlinearity and a convenient way to plot such data. In Fig. 3a, we show an exaggerated schematic of 3 typical situations observed with silicon solar cells in our measurements. In the ideal case, we observe a linear relationship between the light intensity and the cell photocurrent. If plotted as a function of the ratio of current to light intensity vs. current, a constant plot is observed as shown by the dotted red line in Fig 3b. A majority of Si solar cells that we have measured, however, behave as shown by the black curve. For these cells, the light intensity rises super-linearly with respect to the current at low intensity but then trends linear at higher intensities. The point of transition from nonlinear to linear behavior varies among different cells and is likely related to the material quality and the influence of charge carrier recombination mechanisms. The light intensity for this transition can be as low as 0.0001 sun-equivalent intensity or as high as 0.1 (or more) sun-equivalent intensity. The ratio plot in this case (black curve in Fig 3b) shows a ratio that increases with current and reaches steady state above a certain current or intensity value. Finally, there are rare cases represented by the green curve where one could see a ratio plot that initially rises rapidly with current, followed by a more moderate rise at higher intensities. Some of these cases never show a leveling-off behavior even at the highest intensities at which we have irradiated the cells. Also, these types of cells generally have lower I_{sc} output and inferior current-voltage performance, although clearly these characteristics improve with intensity.

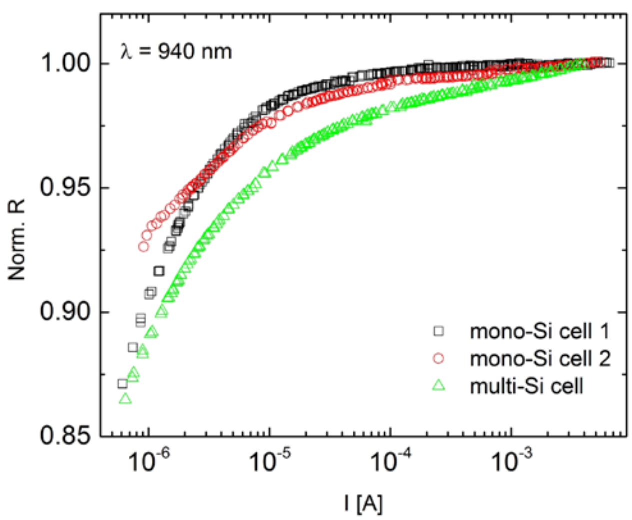

Fig. 4. The ratio of signal to flux plotted as a function of signal for 3 different types of silicon solar cells, with an excitation wavelength of 940 nm. Each cell is 2 cm × 2 cm in dimensions.

C. Measurement Results

We examined the relationship between current and intensity of a large variety of solar cells, including some reference solar cells available for purchase from private calibration laboratories. The results indicate large variations in nonlinear behavior among nominally similar silicon solar cells. Fig. 4, for example, shows the normalized ratio of signal-to-flux plotted as a function of current over a large signal range on a linear-logarithmic scale for measurements with two 940 nm LEDs. Here, the data were collected in multiple overlapping segments of signal so that a large signal range can be probed and plotted. The two mono-crystalline cells behave slightly differently, particularly under the low signal/ low intensity regime, but they both reach a saturating value, i.e., linear behavior at current values > ≈ 10^{-4} A. The multi-crystalline Si cell measurements, however, reveal significantly more nonlinear response at lower signals and do not appear to reach a steady state behavior even at signal values ≈ 10 mA (roughly 0.1 sun-equivalent for these cells). This particular cell shows that, between the signal levels

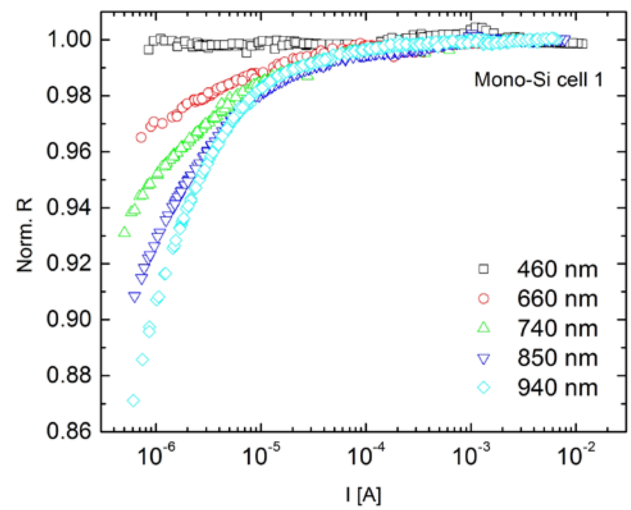

Fig. 5. The ratio of signal to flux plotted as a function of signal for the mono-Si cell 1 at multiple wavelengths.

10^{-6} A to 10^{-4} A, there is approximately a 10 % nonlinearity, meaning the output of the device is 10 % lower at the lower signal level. Furthermore, the data show that at higher light intensities, the spectral responsivity (which is proportional to the external quantum efficiency of these devices) is larger than that at lower intensities. This finding has major implications for spectral response measurements. Most research groups perform such measurements using the differential spectral response method, where a monochromator and mechanical chopper are used to sweep the wavelength across a spectral range and measure the I_{sc} of the cell in response to this modulated excitation. The monochromatic light intensity in most setups is very low, typically on the order of 1 µ*W* to 20 µ*W* of incident power. These conditions will yield a device spectral response/EQE that is not representative of the spectral response under the standard reporting conditions, i.e., air mass 1.5, 1 kW/m^2 intensity. In such cases, a DC-operated light bias needs to accompany the modulated light source to ensure that the cell is operating within the linear regime.

For the combinatorial measurements presented here, the main uncertainty component is associated with the repeatability of the current sourcing to the LEDs and the resulting signal from the cell [4]. This repeatability uncertainty is roughly 1 %, therefore allowing this method to be used to examine nonlinear relations on the order of a 1 % change. All the other sources of uncertainty, including the LED stability and statistical variations are minimal.

Fig. 5 shows the nonlinear behavior of the mono-crystalline cell 1 for different excitation wavelengths. These data indicate that nonlinearity is dependent upon the wavelength of light. At lower wavelengths, e.g., 460 nm, the nonlinearity is nonexistent over the entire range probed here, but the nonlinearity becomes more severe at low signal levels under higher wavelength LED light. Although the nonlinearity for this cell occurs under very low light conditions and improves at higher intensities (cell becomes linear at all wavelengths), the implications of these results in practical applications are notable. For example, if such a cell were to be employed in indoor PV-powering applications [5], one indeed should be concerned with nonlinear behavior under low light conditions, particularly with light sources that contain more near-IR components in their emission spectra. As for outdoor installed PV, such types of cells would obviously have lower outputs/power conversion efficiency under low light conditions, i.e., cloudy skies, and early or late in the day, than they would closer to the SRC illumination conditions.

IV. CONCLUSIONS

Nonlinear behavior of current with light intensity in various types of silicon solar cells were measured by an LED-based combinatorial flux addition method, taking advantage of spectral and light intensity level control afforded by use of LED sources. The combinatorial measurements allow for calculation of the incident flux, and hence the ratio of signal to flux, by setting and solving an overdetermined linear system of equations. Our results indicate that linearity is strongly dependent on both the intensity of the light source and the wavelength of the illumination.

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