Frequency response of the external quantum efficiency in multijunction solar cells

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Abstract

The frequency dependence of the external quantum efficiency (EQE) of high-quality multijunction solar cells was examined by the modulated photocurrent spectroscopy method via an optical setup comprised of a light-pipe-coupled compact LED array. The optical excitation was achieved through sinusoidal electrical modulation of an appropriate LED by a custom-designed, high bandwidth amplifier. We observed unique features in the amplitude and phase data of the EQE frequency sweeps that are very sensitive to various subcell parameters and light bias conditions. These features are discussed extensively within the context of an AC equivalent circuit model, showing remarkable agreement between the experimental data and the proposed model.

1. Introduction

As high-efficiency multijunction solar cell (MJSC) technologies achieve record efficiencies [1,2], the complexity of the internal structure and inner workings of the cells also reach new levels. A suite of opto-electronic characterization techniques has been used in the past to explore the various characteristics of these cells. Extensive light bias and voltage bias dependent external quantum efficiency measurements [3–10], detailed current-voltage (I–V) characterization [11], and electroluminescence measurements [12,13] have traditionally been used to elucidate various artifacts and phenomena such as low shunt resistance effects [3,6,7,9,14,15], reverse breakdown voltage [3,4,16], and luminescence coupling (LC) [10,11,17–21] in these devices. Furthermore, new techniques such as electric modulus spectroscopy [22] have been used to observe charge coupling effects in Ge-based triple junction solar cells. However, modulated photocurrent spectroscopy (MPCS) [23–25], which probes the frequency dependence of the AC photogenerated current in response to modulated light excitation, has not been explored in MJSCs previously.

In this work, we have applied the MPCS technique to high-quality triple junction GaInP/GaAs/GaInNAs solar cells [26,27] by designing and constructing a light-pipe-coupled LED array, consisting of various quasi-monochromatic LEDs that can be selected to be either electrically modulated (sinusoidal) or DC-driven. This setup has allowed us to perform
frequency-dependent AC photocurrent measurements under appropriate light bias conditions for each subcell over a frequency range of 10 Hz to 200 kHz. When this photocurrent response is normalized by the radiant power of the incident modulated light, a frequency-dependent spectral response is obtained, which can be converted to the external quantum efficiency (EQE) of the device as a function of the incident excitation frequency. At a fixed low frequency, this measurement, which is sometimes referred to as the differential spectral response method, is commonly performed by many research groups. An important question arises as to how the frequency of the chopper or the optical modulator affects the EQE results. Furthermore, since these devices are comprised of multiple subcells, each with its own unique electrical response, one could imagine that fundamental device parameters such as capacitance and resistance of each cell would affect the extraction of charge from the whole device. Therefore, our main objective in using the MPCS technique was to study what sorts of phenomena affect the frequency response of these measurements and whether this method can be used reliably to extract the various subcell parameters.

In previous work in semiconductor devices or photoelectrochemical cells, various versions of MPCS have been used to determine energy distribution of traps in the material’s band gap [28], charge transfer and recombination at interfaces [24,29], and the dynamics of charge transport and collection in devices [30]. Our investigation of multijunction solar cells using this technique has revealed that, depending upon the interplay of light biasing conditions and the junction parameters, interesting features can be observed in the frequency response of both the amplitude and the phase of the photocurrent. For the sake of simplicity, the cells were operated in such a way as to minimize the light coupling effects, particularly between the top and the middle, and the middle and the bottom junctions. A careful examination of the data within the framework of an equivalent circuit model reveals a wealth of information about each subcell within the stack.

2. Experimental details

In order to perform the frequency-dependent modulated photocurrent measurements, an LED array with 12 high-power LEDs was designed and fabricated on an aluminum-clad PCB board. Each LED is electrically isolated from its neighbor and can be separately and simultaneously driven by a controller. A diagram of the experimental setup is shown in Fig. 1. A function generator is used in conjunction with a custom high-bandwidth power amplifier to provide a sinusoidal AC signal to a given LED, while a separate multi-channel LED controller provides DC input signals to 2 (or more) LEDs at the same time. A solid borosilicate glass light pipe in the form of a frustum is mounted in front of the array to couple, as effectively as possible, a large portion of the radiation into the guide, as well as to provide a uniform illumination spot at the sample location (the exit port of the light pipe). The cell’s output is connected to a high speed transimpedance amplifier, which in turn is connected to a lock-in amplifier, which provides the amplitude and relative phase of the signal. This lock-in is synchronized with the function generator, and the whole system is controlled and automated by a computer program. The function generator’s frequency is swept, generally in a logarithmic fashion, from 10 Hz to 200 kHz, resulting in a change in the LED’s modulation frequency and the frequency of the AC current signal. Amplitude and phase of the photocurrent are then recorded as a function of this frequency. A second
consecutive measurement is performed on a calibrated high-bandwidth detector to obtain the intensity of the incident light and its frequency response, because the LED output at higher frequencies decreases slightly, hence the need for monitoring. In order to avoid a wavelength dependence with temperature of the LEDs, a water chiller is used to cool the LED array plate to approximately 15 °C, as shown in Fig. 1.

Figure 2. shows a photo of the optical segment of the setup. On the left side of the image, the LED array can be seen, slightly pulled back from the entrance of the light guide for a better visual. Of the 12 mounted LEDs, eight have nominal emission wavelengths of 460 nm, 523 nm, 590 nm, 623 nm, 660 nm, 740 nm, 850 nm, and 940 nm, and another four are white or broadband LEDs. In the image shown, both the 523 nm and 623 nm LEDs are turned on, producing a yellow color on the sample mounting plate due to the homogenization of the green and red light rays passing through the light guide (shown in the center, encased in a 3D printed holder). The uniformity is at its best at the exit plane of the light pipe. The dimensions of the entrance port and the exit port are 40 mm × 40 mm, and 50 mm × 50 mm, respectively, with a total guide length of 140 mm. All surfaces are highly polished to maximize total internal reflection and minimize radiation loss.

The solar cells used for this study were GaInP/GaAs/GaInNAs triple junction cells, with an illuminated active area of 31.6 mm$^2$. Throughout this work, the GaInP will sometimes be referred to as the top junction, the GaAs as the middle junction, and the GaInNAs as the bottom junction. Closely-matched isotype cells of each kind were also available for individual capacitance or quantum efficiency measurements.

The modulated photocurrent measurements with LEDs explore the frequency dependence of the EQE for a fixed single wavelength. Prior to these measurements, the active region of each junction was also characterized by performing spectral response measurements on the cell by a monochromator-based system as shown in Fig. 3. These measurements show the spectral region of responsivity for each junction so that LEDs with appropriate wavelengths can be selected for measuring the frequency response of each junction separately. The effects of light coupling between the top and the middle junction and between the middle and the bottom junction were minimized during the MPCS by controlling the intensity levels of the bias lights [17]. In the case where the modulated light is applied to the top junction while the middle and bottom junctions are DC light-biased, the 460 nm LED served as the probing light source and the 740 nm and 940 nm LEDs were used as DC bias lights in the setup of Fig. 1. For measurements on the active region of the middle cell the 740 nm LED was selected as modulated light, and the other two LEDs provided the bias light.

3. Theoretical model

An equivalent circuit model (ECM) for the MPCS measurements on the triple junction solar cell is presented in Fig. 4, where we built upon the double junction version in reference [10]. $\tilde{I}_T$, $\tilde{I}_M$, $\tilde{I}_B$ represent the AC photocurrents generated in each junction. $R_T$, $R_M$, $R_B$ their dynamic resistances (which might depend on the DC light bias currents), $C_T$, $C_M$, $C_B$ the junction capacitances, and $R_S$ the series resistance. In addition, two dependent current sources, $\eta_1 \tilde{I}_r$ and $\eta_2 \tilde{I}_r$ are incorporated in this model to account for possible luminescence
coupling from the top junction to the middle junction, and from the middle junction to the bottom junction, respectively. $I_{r1}$ and $I_{r2}$ are recombination currents in the top and the middle junctions and $\eta_1$ and $\eta_2$ are luminescence coupling constants.

The general solution for the circuit-extracted current, $\widetilde{I}_{SC}$, in terms of the relevant parameters can be found by applying Kirchhoff’s current and voltage laws to the circuit. The final result is shown in Eq. (1) below:

$$
\widetilde{I}_{SC} = \frac{I_T \left( Z_T + \eta_1 \frac{Z_M Z_B}{R_T R_M} + \eta_2 \frac{Z_M Z_B}{R_T R_M} \right) + \widetilde{I}_M \left( Z_M + \eta_2 \frac{Z_M Z_B}{R_M} \right) + \widetilde{I}_B Z_B}{Z_T + Z_M + Z_B + R_s + \eta_1 \frac{Z_M Z_B}{R_T} + \eta_2 \frac{Z_M Z_B}{R_M} + \eta_1 \frac{Z_M Z_B}{R_T R_M}},
$$

where

$$
Z_i = \frac{R_i}{1 + j\omega C_i R_i} (i = T, M, B),
$$

In the absence of light coupling and taking as an example the case where the modulated light is applied to the top junction while the middle and bottom junctions are DC light biased, i.e., similar to EQE measurement conditions for the top junction,

$$
R_j = \frac{n k_B T}{q} \frac{1}{I_j} = \frac{n V_T}{I_j} (j = M, B),
$$

and Eq. (1) is simplified to:

$$
\frac{\widetilde{I}_{SC}}{I_T} = \frac{Z_T}{Z_T + Z_M + Z_B + R_s}.
$$

In these equations, parameter $n$ is the diode ideality factor, $k_B$ the Boltzmann constant, $V_T$ the thermal voltage ($\approx 25$ mV at room temperature), and $I_j$ the DC light bias current generated in the middle/bottom junction. As mentioned earlier, $\widetilde{I}_T$ represents the AC photocurrent generated in the top junction due to the modulated light excitation, meaning $\widetilde{I}_T \propto \tilde{E}_T$, the modulated light intensity. Therefore, $(\widetilde{I}_{SC}/I_T) \propto (\widetilde{I}_{SC}/\tilde{E}_T) = \tilde{R}_T$, where $\tilde{R}_T$ is the differential spectral responsivity of the top junction. Since $\tilde{R}_T$ is treated as an internal current source, $\tilde{R}_T$ already takes into account the effect of surface reflections. It is important to note that the ratio $\widetilde{I}_{SC}/I_T$ actually represents an apparent internal quantum efficiency (IQE) [10] rather than a true IQE of this cell. The true IQE is a measure of how many electrons are extracted per absorbed photons under steady-state conditions, whereas as $\widetilde{I}_{SC}/I_T$ is an apparent IQE that at low frequencies approaches the true IQE and at higher
frequencies suffers from device-related artifacts. For comparison with the experimental data we have multiplied this value by a fixed constant so that it can represent the apparent EQE at the excitation wavelength probed.

A similar result holds for the cases when the modulated light is applied to the middle or bottom junctions, by simply exchanging $Z_T \leftrightarrow Z_M, Z_B$ in the numerator. It can be shown from Eq. (2) that in the low frequency limit where $\omega \rightarrow 0$, $Z_i \rightarrow R_i$, therefore we obtain:

\[
\frac{\tilde{I}_{SC}}{I_T} = \frac{R_T}{R_T + R_M + R_B + R_S} \approx 1. \tag{5}
\]

The last step follows from the approximation $R_T \gg R_M, R_B, R_S$ when the top cell is in reverse bias. On the other hand, in the high frequency limit $\omega \rightarrow +\infty$, $Z_i \rightarrow 1/j\omega C_i$, and if we consider a negligible series resistance, then we find:

\[
\frac{\tilde{I}_{SC}}{I_T} = \frac{1}{1 + \frac{Z_M}{Z_T} + \frac{Z_B}{Z_T}} \rightarrow \frac{1}{1 + \frac{C_T}{C_M} + \frac{C_T}{C_B}}. \tag{6}
\]

Also, depending on the ratio $I_M/I_B$, one of the following intermediate behaviors between the last two may arise:

\[
\text{Re} \left( \frac{\tilde{I}_{SC}}{I_T} \right) \rightarrow \begin{cases} \frac{1}{1 + \frac{C_T}{C_M}}, & \text{if } I_B \gg I_M, \\ \frac{1}{1 + \frac{C_T}{C_B}}, & \text{if } I_M \gg I_B. \end{cases} \tag{7}
\]

where the first case can be shown by expanding out the complex form of Eq. (4), which describes the complex form of IQE, and noting that when $I_B \gg I_M, R_M \gg R_B$ and vice versa for the second case. The easiest way to achieve this task is to first solve it numerically using a given set of parameters, and then to separate the real and imaginary terms, as in $\tilde{I}_{SC}/I_T = X(\omega) + jY(\omega)$, with $j$ the imaginary unit. The magnitude of the IQE is given by $R = \sqrt{X^2 + Y^2}$, and the phase angle $\phi$, which represents the phase lag between $\tilde{I}_{SC}$ and the modulated light, is given by $\tan(\phi) = Y/X$. The results of such a calculation for a set of parameters are plotted in Fig. 5, where the left Y-axis shows the magnitude IQE (apparent) and the right Y-axis the phase lag angle, expressed in degrees. For this plot the middle DC bias current was kept fixed at 1 µA while the bottom DC current was increased from 1 µA to 2 mA, and the series resistance was taken to be 50 Ω for exemplification purposes. It can be seen from the plot that the phase presents a resonant behavior at two different frequencies in general. The values for which these resonant peaks occur are found to be:

\[
\omega_j^{\text{min}} \approx \frac{1}{R_j C_j} \propto I_j(j=M, B). \tag{8}
\]
where the last step follows from Eq. (3). In other words, an increase in the DC current generated in either junction produces a shift towards higher frequencies for the resonant peak. By taking the ratio of the imaginary and the real parts of Eq. (4), it can be shown that when there is no series resistance present, the phase goes to zero in both the high and the low frequency limits. On the other hand, a non-zero series resistance causes a drop in the amplitude from the value in Eq. (6) to zero, and makes the phase rotate from 0° to −90° in the high frequency limit.

Also, as $I_B$ increases and reaches the condition $I_B \gg I_M$ the limit $(1 + C_T/C_M)^{-1}$ expected from Eq. (7) appears in the plot. Using this result, the experimental data can reveal the ratio $C_T/C_M$ and by using Eq. (6), $C_T/C_B$ could also be extracted.

In addition, as long as the condition $R_T \gg R_M, R_B, R_S$ is met, the model is quite insensitive to the specific value of $R_T$, and in fact its value will only affect the low frequency region, something already expected from Eq. (5). Finally, the $I_B = 2$ mA curve shows that when $R_S \neq 0$ the IQE drop to zero might occur before the limit in Eq. (6) since $R_B$ is such that $1/R_S C_T < 1/R_B C_B$, and so the latter would never happen in such a case.

4. Experimental results and modeling

Starting from the amplitude and the phase data obtained from the lock-in measurements for both the solar cell and the reference detector, the EQE and the net phase can be calculated. This calculation is very similar to the generic EQE calculations in the differential spectral response method, with the exception that both the real and the imaginary part of the measured photocurrent, at each frequency, need to be utilized. The ratio of current to light power provides the spectral responsivity, from which EQE amplitude and phase are extracted. Figure 6 shows the results obtained from the top cell measurements (scatter points, the 460 nm LED as pulsed light, the 740 nm and the 940 nm LEDs as bias light), as well as the model predictions of Eq. (4) (solid lines). As before, the left Y-axis represents the external quantum efficiency and the right Y-axis the phase, expressed in degrees. For each setting, both the model predictions and the measurements were scaled to the low frequency EQE value obtained from the monochromator setup at the wavelength 460 nm, while a fixed value of $\approx 2.5^\circ$ was universally subtracted from the phase data to account for the unphysical non-zero phase at low frequencies related to a small phase lag in the instrumentation. Setting 1 to Setting 4 correspond to different DC light bias conditions, which are expressed in Table 1 in terms of the LEDs’ light intensity at the cell location, as measured by a calibrated spectroradiometer.

The fit of the model to the data was achieved by writing a regression analysis code that calculates the sum of the squares of the residuals between the model and the data and minimizes it over many iterations for all the fit parameters. The 5 parameters that need to be solved for in this case are $C_T, C_M, C_B, I_M$ and $I_B$ while $R_T$ was estimated from individual resistance measurements but kept fixed, since they are, as pointed out earlier, quite insensitive with respect to their specific values as long as $R_T \gg R_M, R_B, R_S$. To obtain the best parameters, we fit all 4 data curves simultaneously, so that one set of capacitance values can be applied to all 4 curves, while the current parameters were allowed to change for each
curve. Table 3 shows the final parameters used for the fits. Overall, the model can be successfully used to fit the data and extract the parameters listed in Table 3. Section 5 will address the uniqueness issue of the fit parameters and certain assumptions in detail.

As can be seen from Fig. 6, the EQE drop from its peak value occurs around the same frequency where the phase minimum is observed, and the resonant value shifts towards higher frequencies, consistent with Eq. (8) when the DC currents generated in the junctions increase (compare for instance the red vs black curve). In this case, no intermediate behavior as predicted by Eq. (7) is observed since any attempt to meet the condition \( I_M \gg I_B \) or \( I_B \gg I_M \) results in either the middle or bottom junction becoming current-limiting, but the high frequency limit of Eq. (6) can clearly be observed. Also, a sudden drop in the EQE after this limit, i.e., at a frequency \( \omega \approx 5 \times 10^5 \text{ rad/s} \) indicates the presence of a non-zero series resistance. A quick look up in the current-to-voltage transimpedance amplifier’s specification data reveals an input impedance of 50 \( \Omega \), so this value needs to be taken into account in the model and it ends up being the most dominant contribution to \( R_S \).

Frequency dependent EQE measurements were also performed on the middle junction, with various DC illumination conditions on the top and the bottom subcells and the results are plotted in Fig. 7. The irradiance of the LEDs used as light bias is shown in Table 2 while the fit parameters for the model are added to Table 3. Recall that all the theoretical predictions can be adjusted for this case just by setting \( M \leftrightarrow T \) in the results of Section 3.

In this case Settings 5 and 6 actually show the predicted behavior by Eq. (7) and examination of Table 3 makes this clear. According to the model, the average ratio of the DC currents generated in each junction is \( I_B/I_T \sim 7 \) for these two configurations (Settings 5 and 6 only), compared to an average ratio of \( I_B/I_M \sim 1.5 \) for Settings 1 to 4 above. Therefore, in this case, the condition \( I_B \gg I_T \) is met and the limit \( (1 + C_M/C_T)^{-1} \) becomes visible in the data. Notice, that the ratio of the LEDs intensities used in these two settings is similar to the ones that were used before (see Table 2).

The measurements and modeling results presented here demonstrate that the AC/DC or the differential EQE measurements have notable frequency-dependent features that depend on internal device workings such as the subcell capacitances, dynamic resistances and the total photocurrents generated in each junction. By utilizing a relatively simple equivalent circuit model, we have successfully explained what these features are and how they can be changed from one condition to another. Here, we have limited ourselves to cases of no LC between the various junctions, the existence of which complicates the frequency response of EQE even more. This work also demonstrates that the measurement frequency is very important in determination of the DC-limit EQE (i.e., EQE as \( \omega \to 0 \)). For example, both Fig. 6 and Fig. 7 indicate that an EQE measurement with a pulsing (or chopping) frequency greater than 1 kHz (6.28 kRad/s) can result in a substantial error in determining the magnitude of the EQE of a given junction. This conclusion is due to the sharp drop in the maximum value of EQE at such a frequency, and in fact does significantly depend on the light bias currents generated in each junction. Certain other device configurations may even exhibit a shorter corner frequency than does the case described here and hence the measurement must be performed at a much lower frequency in order to get accurate spectral responsivity results. A
final question that arises is how physically accurate or relevant the fit parameters are, an issue that is discussed next.

5. Discussion of the fit parameters

We explored the question of the uniqueness of the fit parameters extensively by applying the least squares regression method over a wide range of parameter values. The first step in this process involved looping through a set of current and capacitance values, and in each step determining the sum of the least squared residuals for all configurations. Once a minimum is found, the set where the solution is looked for, is now taken as an interval centered on the values where this minimum happened, and the process is repeated. After several steps (10–20 was often sufficient for finding a convergent solution) the output of the script provides the final capacitance and current values that gives the best fit to the data and reports the absolute lowest sum of the squared residuals. For the top cell measurements of Fig. 6, we observed that a best fit can be obtained for all 4 curves if all the 5 fit parameters were allowed to be free and unrestricted over large intervals of values. However, the fit parameters in this case would not be unique because we could easily fix one of the parameters and obtain a good fit to the data with 4 different set of parameters. Next, we fixed either \( C_T \), \( C_M \), or \( C_B \) to a value that we had previously determined from iso-type cell C-V measurements, effectively reducing fit parameters from 5 to 4. In this case, we observed that we could indeed obtain a unique set of 5 parameters, regardless of which one of these 3 capacitances were fixed. This indicated that a convergence around a unique set of 4 parameters was taking place. All the values in this case are consistent with iso-type cell measurements, with \( I_M \) and \( I_B \) revealing what the operating DC current inside each junction is. These findings strongly suggest that a best and unique solution can be found with this model as long as one of the five fit parameters is known from a secondary measurement. Since it is difficult to know the operating current from any other measurement, the simplest option is to determine one of the capacitances from an iso-type cell measurement or estimate it from published results and use that value to allow for convergence of the rest of the fit parameters.

For the middle cell results and modeling, we observed a similar behavior. As long as one of the three capacitance values could be determined and fixed, the model shows convergence and uniqueness of the fit parameters. It should be mentioned that the capacitance and the photocurrent values depend on the bias voltage established across each subcell. In the cases presented here, the two light biased junctions operate in the forward bias region, whereas the current limited junction operates in reverse bias since the net voltage across the entire stack is kept at zero. Therefore, the extracted photocurrent values are generally smaller than individual junction-generated short circuit current, and the capacitance values are either a reverse-biased value (the current limited subcell), or a forward-biased value (the light biased subcells). Therefore, the use of the equivalent circuit model provides for a unique way to obtain some information regarding certain device parameters.

6. Conclusions

We used the technique of modulated photocurrent spectroscopy to study the amplitude and phase behavior of the external quantum efficiency of a triple junction solar cell as a function
of the light excitation frequency. It was observed that an equivalent circuit model, incorporating the basic electrical and optical elements of each subcell in series, can explain all the EQE features observed in these measurements. Furthermore, applying this model to the data shows how different parameters affect different frequency regions of the EQE curve. In addition to our primary goal of explaining the frequency response of the EQE, we also explored the question of the uniqueness of the fit parameters and whether the model can be used to extract the true values of these important physical quantities. Our regression analysis concludes that if the number of free parameters is reduced from five to four, through say one secondary measurement, then significant confidence is established regarding the uniqueness of the fit parameters.

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Fig. 1.
Experimental setup used for the measurements. Both an AC and DC source are taken as an input of the LED array, which illuminates the sample through a glass light pipe. A high speed lock-in amplifier measures the amplitude and relative phase of the signal, and those values are then recorded on a computer.
Fig. 2.
Optical segment of the experimental setup. Both 523 nm (green) and 623 nm (red) LEDs are shown turned on, producing a yellow color at the sample mounting plate.
Fig. 3.
External quantum efficiency as a function of wavelength for the GaInP/GaAs/GaInNAs solar cell.
Fig. 4.
Equivalent circuit for the MPCS measurements performed on the triple junction solar cell. The AC sources represent the currents generated in the junctions, while the dependent current sources account for any possible light coupling.
Fig. 5.
Predicted internal quantum efficiency as a function of angular frequency. Here $R_S$ was taken to be 50 $\Omega$, while $I_M$ was kept fixed at 1 $\mu$A. The phase presents a resonant behavior and the IQE reaches well-defined values in the high and low frequency limits.
Fig. 6.
Results obtained from fitting the top cell measurements to the theoretical model, both being scaled to the EQE measured by the monochromator system. Settings 1 to 4 correspond to different light bias conditions on the cell (see Table 1).
Fig. 7.
Results obtained from the middle cell measurements superposed on the theoretical model predictions, both being scaled to the EQE reported by the monochromator system. Settings 5 to 8 correspond to different light bias conditions in the cell (see Table 2). A fixed value of $\approx 1^\circ$ was universally subtracted from all the phase data to account for constant phase offset.
Table 1

Intensity of the LEDs used as light bias for the top cell measurements. The intensity of the pulsed light in this case was 0.9 W/m² for the 460 nm LED.

| Setting | 740 nm LED (W/m²) | 940 nm LED (W/m²) |
|---------|-------------------|-------------------|
| Setting 1 | 3.41              | 4.23              |
| Setting 2 | 4.31              | 5.09              |
| Setting 3 | 3.41              | 2.38              |
| Setting 4 | 2.25              | 4.23              |
Table 2

Intensity of the LEDs used as light bias for the middle cell measurements. The intensity of the pulsed light in this case was 0.5 $W/m^2$ for the 740 nm LED.

|       | 460 nm LED (W/m$^2$) | 940 nm LED (W/m$^2$) |
|-------|----------------------|-----------------------|
| Setting 5 | 5.29                | 6.49                  |
| Setting 6 | 6.28                | 6.98                  |
| Setting 7 | 12.21               | 10.05                 |
| Setting 8 | 5.29                | 4.23                  |
Table 3

| Parameters | Top cell measurements | Middle cell measurements |
|------------|----------------------|--------------------------|
| $R_T$ (Ω)  | 2.18×10^6            | -                        |
| $R_M$ (Ω)  | -                    | 8.2×10^5                |
| $C_T$ (nF) | 20.83                | 41.59                    |
| $C_M$ (nF) | 48.88                | 13.2                     |
| $C_B$ (nF) | 31.15                | 33.35                    |
| $I_T$ (µA) | -                    | 20.52                    |
| Settings   | 5–8                  | 34.27                    |
|            | 1–4                  | 141.53                   |
|            | 5–8                  | 22.1                     |
| $I_M$ (µA) | 95.46                | 212.47                   |
| Settings   | 1–4                  | 328.28                   |
|            | 5–8                  | 86.56                    |
| $I_B$ (µA) | 110                  | 20.52                    |
| Settings   | 5–8                  | 34.27                    |

In all cases, the series resistance was 50 Ω, corresponding to the input impedance of the transimpedance amplifier. For the top cell measurements, $C_B$ was fixed while $C_T$, $C_M$, $I_M$, and $I_B$ were solved for using the least squares regression analysis, and for the middle cell measurements, $C_T$ was fixed while $C_M$, $C_B$, $I_T$, and $I_B$ were determined by the fitting process. In either case, $R_T$ or $R_M$ were kept fixed after their initial estimates from isotype cell measurements.