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Fast Optical Measurement System: Ultrafast external quantum efficiency measurements on silicon solar cells

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ABSTRACT

Measuring the external quantum efficiency (EQE) of a solar cell is a standard method to gain deeper insights into its opto-electrical properties. For the case of crystalline silicon solar cells, the EQE of a solar cell is often used to assess the quality of the emitter and the passivation scheme. However, the standard EQE measurement method employs a monochromator which means that several minutes are typically needed to complete a single measurement. In academic environments this can form a bottleneck in the research output, while in industrial environments with production speeds of at least 1800 wafers/hour EQE measurements cannot be readily used. In this work, we introduce a new patented characterization tool which we call the Fast Optical Measurement System (FOMS). When using the FOMS, it becomes possible to measure the EQE of amorphous and crystalline silicon solar cells about 3 orders of magnitude faster when compared to a conventional monochromatic measurement. This means that a measurement of the full visible/near-infrared (VIS/NIR) spectrum can be done in 1–10 s, without compromising on accuracy. Additionally, the FOMS can also be used to perform ultrafast reflectance/transmittance once further add-ons to the system are implemented. This opens a path to many optical applications, also outside the photovoltaics field, where fast and accurate broadband measurements are needed.

1. Introduction

Together with the current-voltage (IV) characterization of a solar cell, the determination of the external quantum efficiency (EQE) is fundamental to photovoltaic research. Although EQE measurements are commonly used in academia to evaluate the spectral response of a solar cell, *e.g.* to evaluate the quality of the emitter or the used passivation scheme, a conventional EQE system cannot be used in an industrial production environment. The reason for this limitation is the needed measurement time which is typically much longer than what is compatible with the speed of 1800 wafers/h (or more) at which crystalline silicon (c-Si) solar cells are industrially produced. More specifically, conventional EQE measurements require a typical measurement time in the order of minutes to resolve an acceptable EQE spectrum in the visible/near-infrared (VIS/NIR) part of the spectrum due to the use of a monochromator and a lock-in amplifier [1]. This means that the measurement time scales with the number of points (wavelengths) measured and more time is needed for those points in the spectrum where the solar cell has a weak response.

As an alternative to this established, but relatively slow way of measuring the EQE spectrum, several groups have proposed faster alternatives. The first proposed alternative systems included a series of modulated laser light sources, basically as a variation to the light beam-induced current (LBIC) measurement technique [2,3]. Although this did enable extremely fast measurements (< 0.1 s), the EQE spectrum could only be determined at up to five different wavelengths which were given by the wavelengths of the used lasers, so in terms of accuracy this could not match the standard monochromatic measurement which typically includes several tens of points in the VIS/NIR wavelength range. When LEDs were becoming available at ever more different wavelengths, various groups fabricated LED-based EQE measurement systems, all with measuring speeds of 1–10 s [4–8]. This improved the accuracy expressed in the number of points to several tens and this approach yields an acceptable approximation of the solar spectrum in the sense that the AAA spectral norm can be met [9]. Note that the accuracy of EQE measurements that are conducted with an LED-based system are not compromised by the relatively broad spectral distributions of LEDs when using a filter arrangement that ensures monochromatic illumination from the different LEDs onto the device while the light intensity can be tuned for each type of LED. Due to the monochromatic nature of the source light no prior knowledge of the expected EQE spectrum and the spectral width of the different LEDs is needed when aiming to optimize the accuracy of the EQE measurement.

An alternative approach that involves illumination with white light

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comes from the field of infrared spectroscopy. In 1997, Tomm et al. introduced the use of Fourier transform spectroscopy when using the spectrometer as an excitation source to perform photocurrent measurements on high power laser diode arrays to study their aging process based on changes in the subgap absorption [10]. A few years later, a similar approach was followed by Vaněček and Poruba who named the technique Fourier transform photocurrent spectroscopy (FTPS) and used it to study the quality of the intrinsic absorber layer in hydrogenated nanocrystalline silicon (nc-Si:H) solar cells [11]. Over the years it has been shown that FTPS is a highly precise absorption measurement technique that is an ideal tool in the characterization of defects in and the quality of hydrogenated amorphous silicon (a-Si:H) and nc-Si:H films and solar cells [12–16], as well as perovskite materials [17]. In FTPS, white light from a halogen source is modulated by a Michelson interferometer, as a consequence of which the different wavelengths in the source light are modulated at different frequencies. When illuminating a thin film or a solar cell with this modulated light, the spectral response of the sample can be extracted through inverse Fourier transformation of the photocurrent, since the photocurrent is modulated in the same way as the incident light. It should be realized that the scanning velocity in the spectrometer which is typically used to conduct FTPS measurements causes the photocurrent generated by the solar cell to contain frequency components in the low kHz range when resolving the response of the solar cell in the VIS/NIR part of the spectrum [13,16]. Consequently, the time period of the modulation does not exceed 1 ms. This is not a problem when conducting FTPS measurements on non-crystalline silicon materials, which typically exhibit carrier lifetime values in the 1–10 μs range. Therefore, the requirement that the lifetime needs to be much smaller than the time period of modulation to accurately resolve the absorption spectrum is well satisfied in that case. However, the carrier lifetime in c-Si typically ranges from 0.1 to 10 ms, meaning that it is problematic to measure the EQE of c-Si solar cells with FTPS. This is especially true for c-Si solar cells that exhibit a generally high absorption such as interdigitated back contact (IBC) solar cells [16]. When moving towards lower modulation frequencies this problem can be circumvented, but when doing so with an interferometer this results in an excessive measurement time and effects of mechanical instability in the interferometer are likely to be magnified. Although it is in principle possible to measure the EQE of a solar cell by using an interferometer as light modulator [18], an interferometer is a rather bulky, expensive component. However, the sinusoid-based light modulation scheme that is induced by the moving mirror in an interferometer can be mimicked by visually projecting a sinusoid-based modulation scheme as a sequence of bitmap images onto a so-called Digital Micromirror Device (DMD), as will be explained in the following section. Since DMDs are cheap, mass-produced chips that are commonly used in projectors [19] and DMD hardware control boards with data processing capabilities are readily available [20], there is an interesting potential to use this optical chip as the light modulating element in a fast, accurate, and cost-effective EQE measurement system. Note that another type of spectrometer in which an interferometer is avoided utilizes a liquid crystal display (LCD) as an optical light modulator [21], but given the lower refresh rate of LCDs in comparison to the typical operating frequency of DMDs, it is unlikely that the LCD-based approach could match the DMD-based approach in terms of measurement speed.

2. Experimental details

Motivated by the opportunities provided by the use of a DMD, we introduce the Fast Optical Measurement System (FOMS) here. This system is able to measure the EQE of a solar cell in the VIS/NIR range of the spectrum yielding similar results as the conventional, monochromatic EQE system, but with a measurement time of only 1–10 s and by using white illumination of the sample only. Note that we use a halogen lamp as the white light source in this work, since this type of lamp

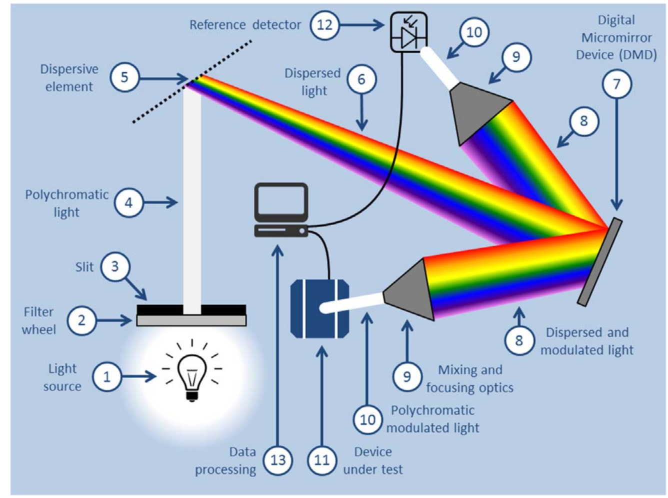

Fig. 1. Schematic layout of the Fast Optical Measurement System in which the light from a source (1) is first directed through a filter wheel (2) and a slit (3). The polychromatic light (4) then illuminates a dispersive element (5), which creates a dispersed light beam (6). This beam illuminates the DMD (7) which acts as a spatial light modulator and naturally produces two light beams (8). These two light beams can be simultaneously directed through mixing and focusing optics (9) such that a polychromatic modulated light beam (10) can be used to illuminate the device under test (11) and the reference detector (12). The final measurement result is obtained by dividing the demodulated photocurrent signals from the device under test and the reference detector by data processing on a computer (13). Reflectance and transmittance measurements can be done by using extra detectors when positioned correctly with respect to the device under test (not shown here).

exhibits a smooth emission spectrum, i.e. without peaked features that can be found in the spectrum of a xenon lamp and to a lesser extent also the spectrum of an array of LEDs. Using a light source with a smooth emission spectrum is desirable, since in that case there is no need to suppress sharp spectral peaks that might otherwise incorrectly appear in the EQE measurement data. A filed patent for this technology explains that this system would not only be able to execute fast EQE measurements, but also to measure the reflectance and transmittance of a sample and finally even the IV-curve, which makes this into a very versatile and fast measuring tool that has applications both inside and outside the field of photovoltaics [22]. Hereby it should be mentioned that the LED-based EQE system described in Ref. [8] makes note of the possibility to modulate white light by using a DMD – although neither a white light source nor a DMD are actually used in the corresponding system implementation described in Ref. [4] – and it can in principle be used for spectral reflectance and transmittance measurements as well. However, in the current work we focus on a demonstration of the EQE-measuring capability of the system.

A schematic overview of the full version of the FOMS is shown in Fig. 1. In our current implementation of this patented system we use a grating as a wavelength dispersive element and a DMD as a spatial light modulator. Since DMD chips rotate by default over one axis between two fixed angle positions, also two light beams are produced. Normally, only the main beam of these two is used and the other one is discarded, while our idea takes advantage of the second light beam to enable simultaneous reference and device under test measurements, which could otherwise be accomplished by using a beamsplitter to create two light beams from the main light beam. Note that this use of the DMD is different from the similar fast DMD-based EQE system presented by Missbach et al. recently, in which the second light beam is not used [23,24]. Also, the problem of higher order components that are introduced by the grating does not seem to be addressed there, since no filter appears in their setup and the measured range (380–750 nm) does not require a higher order correction. Although the principle of measuring the EQE by using a DMD is well demonstrated on a GaInP solar cell, their approach would not work on c-Si solar cells of which the EQE

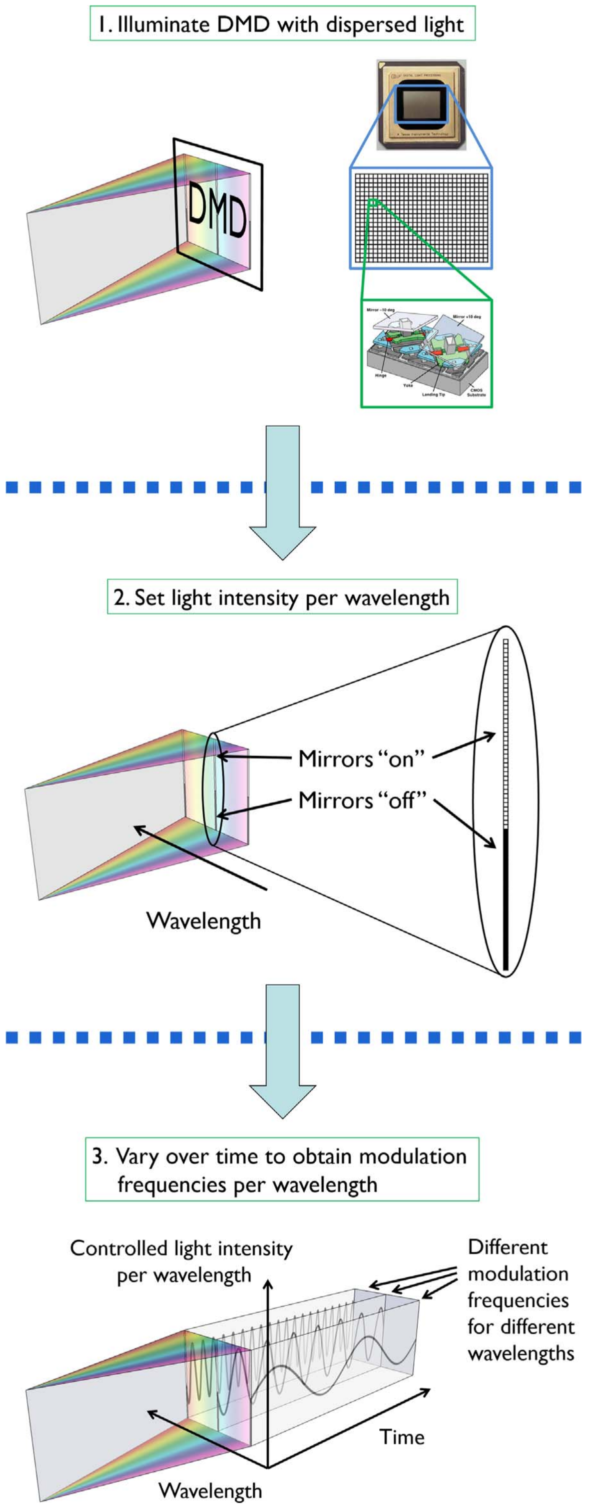

Fig. 2. Schematic visualization of the light modulation principle when mimicking an interferometer: projection of dispersed light onto the DMD (a), selection of number of "on" and "off" mirrors to set the light intensity per wavelength (b), and modulation over time (c).

is typically measured in the VIS/NIR range, since up to three higher orders of light need to be removed there to finally obtain the correct EQE spectrum. To circumvent this problem we employ a set of three optical cut-off filters such that the solar cell response in the 375–1200 nm range can be obtained by measuring it in parts which are spectrally sufficiently narrow so no higher order components of the dispersed light affect the collected photocurrent, i.e. 375–650 nm with the first filter, 650–1000 nm with the second filter, and finally 1000–1200 nm with the third filter. The individual measurements are then stitched together – both for the reference detector and the device under test – so the final EQE curve of the device under test can be obtained.

To understand how the light is modulated in the FOMS it is instructive to consider Fig. 2. First, the dispersed light is directed towards the DMD (a) which has a certain number of mirrors that are arranged in columns and rows. The dispersed light is projected onto the DMD such that the line pattern aligns with the columns and is perpendicularly positioned with respect to the rows. Consequently, each column of mirrors corresponds to a certain wavelength and thus a corresponding modulation frequency, yielding a modulation frequency range of 15–75 Hz for the VIS/NIR spectrum which is the relevant spectral range for EQE measurements on silicon solar cells. Note that this is substantially lower than the modulation frequencies that are used in FTPS which are typically in the low kHz range, so in our approach the time modulation is sufficiently slow to in principle enable proper EQE measurements even on highly absorbing c-Si solar cells, while this is not possible with FTPS [13], as mentioned in the previous section. All the mirrors on the DMD are individually switchable but can all only rotate about one axis, so a mirror is either in the "on" position or in the "off" position. For every wavelength, the intensity of the signal in the first light beam is given by the number of mirrors which are "on", while the signal intensity in the second light beam is given by the amount of "off" mirrors (b). Finally, by projecting a series of images in a sequence onto the DMD over time, different modulation frequencies result for different incident wavelengths (c). When mimicking the typical Michelson interferometer which is used in FTPS, this yields a set of bitmap images representing different sine wave patterns which are first calculated by a computer and then sequentially projected in black and white onto the DMD via a controller which is connected to the computer. The dispersed and modulated light that comes off the DMD is passed through mixing and focusing optics to recombine the light onto the device under test. Note that it is purposely chosen not to recombine the light using a grating or a prism to avoid additional optical losses that subsequently lower the signal-to-noise ratio of the photocurrent generated by the solar cell. Since the modulation scheme is known to be the same as in FTPS, also the measured photocurrent responds in the same way, so the final signal can be obtained by inverse Fourier transformation of the photocurrent. Such a final signal can be obtained for both the device under test and the reference sample, which in our case is an encapsulated and calibrated c-Si solar cell from Fraunhofer ISE. The EQE of the device under test is then equal to the ratio of those two final signals, which is also the final step in calculating the EQE when using a regular monochromatic EQE measurement system.

Note that in FTPS the modulation frequency range, resolution, and measurement time are directly connected by the velocity of the moving mirror in the interferometer. However, in the FOMS, the effects of the moving mirror are simulated by the sequence of bitmap images which is sequentially projected onto the DMD, rendering a decoupling between the modulation frequencies as they appear in the photocurrent signal and the total measurement time. More specifically, the measurement time is determined by the display time of a single image onto the DMD and the number of images, which are independently tuneable variables in the FOMS light modulation scheme that are not available in FTPS. Consequently, in our approach, the resolution is not dictated by the velocity of the moving mirror, but rather by the ratio of the retardation, i.e. the displacement of the simulated moving mirror in the interferometer, and the number of images that are projected onto the DMD. This ratio has been optimized such that the data points in the final EQE curve are spaced about 5–15 nm apart, which is a typical wavelength resolution also seen in conventional monochromatic EQE measurements. Note that this wavelength resolution is achieved by using different optimized sets of bitmap images that are sequentially projected onto the DMD in each of the three individual filter measurements that are used together to obtain the full EQE spectrum. Finally, the display time per projected image can be extended to larger values while still maintaining the same modulation frequency range in the photocurrent, such that reliable measurements on highly absorbing solar cells with significant capacitance could be executed as well.

It should be mentioned that the principle that is used to modulate the light in the FOMS is not vastly different from the ideas behind the first patented LED-based system [4,8] and both systems can be considered to contain a programmable light source. However, our setup is fundamentally different in terms of hardware due to the light modulation that is conducted with the DMD which does not appear in the same form in LED-based systems. Furthermore, we use a single white light source as opposed to a collection of different LEDs to approximate a smooth white spectrum. In the LED approach described in Ref. [8], each different type of LED is driven by a sinusoidal power supply that operates at a different frequency, which enables the use of a Fourier transform to finally derive the EQE from the measured photocurrent that is generated when illuminating the solar cell with all LEDs simultaneously. More specifically, the AC current generated in the solar cell is converted into a digital voltage signal that is comprised of the different frequency components that are associated with the different operating frequencies which each correspond to a different type of LED in the LED array. This means that the voltage waveform linked to each operating frequency (or LED) is converted into an amplitude associated with each of those frequencies (or LEDs). In contrast, in the FOMS, the amplitude of each frequency component is set by the number of “on” and “off” mirrors on the DMD. Note that in the FOMS we do not use a series of separate sinusoidal power supplies that operate at different frequencies, because the chip in which the DMD is packaged already has a drive circuit that can individually address all mirrors on the DMD using simple waveform power supplies to switch each mirror “on” or “off”.

3. Results and discussion

To evaluate the performance of our system both in terms of accuracy and speed we were kindly supplied with a number of single-junction *p-i-n* hydrogenated amorphous silicon solar cells with an active area of ~1 cm^2 and typical initial solar cell conversion efficiencies of 10–11% by the Photovoltaic Materials and Devices (PVMD) group of Delft University of Technology [15,16,25]. An example comparison of an EQE measurement conducted on one of these cells using a conventional monochromatic system and the FOMS is shown in Fig. 3. The same calibrated reference cell was used in both measurement systems to mitigate the influence of the reference cell on the comparison of the two EQE measurement datasets and no voltage biasing or light biasing was employed during the measurements, both in case of the FOMS and

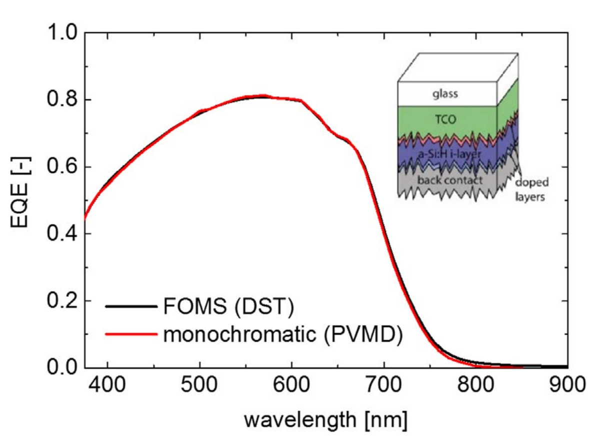

Fig. 3. EQE data of an a-Si:H solar cell supplied by PVMD as measured by Delft Spectral Technologies (DST) with the FOMS and by PVMD with a conventional monochromatic system.

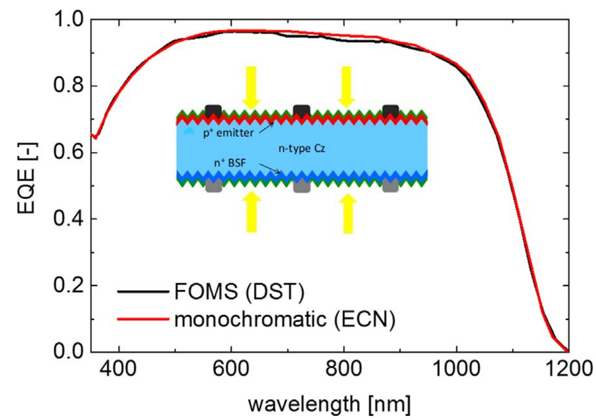

Fig. 4. EQE data of an n-Pasha solar cell supplied by ECN as measured by Delft Spectral Technologies (DST) with the FOMS and by ECN with a conventional monochromatic system.

monochromatic approaches. Note that we have executed the EQE measurements that are shown in this work using both the reference detector and the device under test in the same position by simply alternating them, which is common practice in all other types of EQE measurements as well. When comparing the conventional monochromatic and FOMS approaches in Fig. 3, it is clear that the difference between the two datasets is very small, which demonstrates the suitability of the proposed fast method for measuring the EQE of a-Si:H solar cells.

To further assess the determination of the EQE of solar cells by the FOMS we also measured a set of n-Pasha c-Si solar cells fabricated on 6-inch pseudo-square Cz wafers provided by ECN. This type of solar cell is an *n*-type based bifacial solar cell with typical conversion efficiencies of ~21% [26,27]. Despite the larger spectral range that needs to be measured for this solar cell with respect to the a-Si:H solar cell due to the difference in bandgap of a-Si:H and c-Si, there is a good match in the EQE data between the two measurement approaches, as is shown in Fig. 4. Hereby it should be noted that the measurement conditions between the two setups are rather difficult to replicate, since the sample chucks in the two systems need to have the same spectral reflectivity if one wants to make a fair comparison between EQE measurements on bifacial solar cells. Although care was taken to use again the same reference cell in both measurements, the brass chuck that was used in the monochromatic measurement was not physically the same one as was used in the FOMS for the data shown here. This might explain small differences in the EQE data in the NIR wavelength range, but since the EQE data mainly differ in the 650–900 nm range where the c-Si nearly fully opaque, it is unlikely that the reflectivity of the brass chuck has a significant impact on the EQE values in that spectral range. However, the differences between the two datasets still fall within the uncertainty of the sensitivity values of the calibrated cell, which means that the differences in the data are not convincingly significant.

Finally, we also compared the spectral response of n-PERT c-Si solar cells provided by imec and fabricated on 6-inch pseudo-square Cz substrates. This is a monofacial *n*-type based solar cell with typical conversion efficiencies of ~22% [28,29]. Also for this solar cell type it is obvious from Fig. 5 that the EQE data obtained from the FOMS match very well with the data obtained from the conventional monochromatic system. In fact, the differences are so small that it is difficult to assess them based only on the EQE curves. Therefore, the relative difference in EQE data is plotted on the right axis as $\Delta EQE = (EQE_{FOMS} - EQE_{monochromatic}) / EQE_{monochromatic} \cdot 100\%$. From this data representation it is clear that the relative difference between the EQE values obtained from the two measurement methods does not exceed ± 0.5% in almost the entire VIS/NIR range. Only near the far edges of the EQE curves the relative EQE difference reaches up to ± 2%, which is still well below the uncertainty in sensitivity values

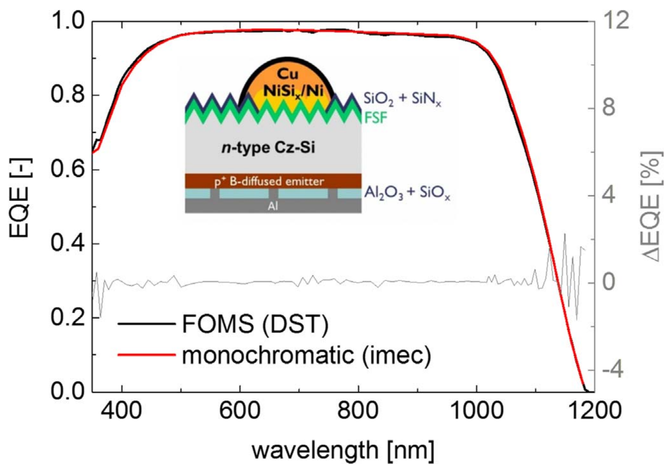

Fig. 5. EQE data of an n-PERT solar cell supplied by imec as measured by Delft Spectral Technologies (DST) with the FOMS and by imec with a conventional monochromatic system. The small relative difference between the EQE spectra obtained from the average of five individual measurements with the FOMS with respect to the monochromatic measurement illustrates the high accuracy of the FOMS.

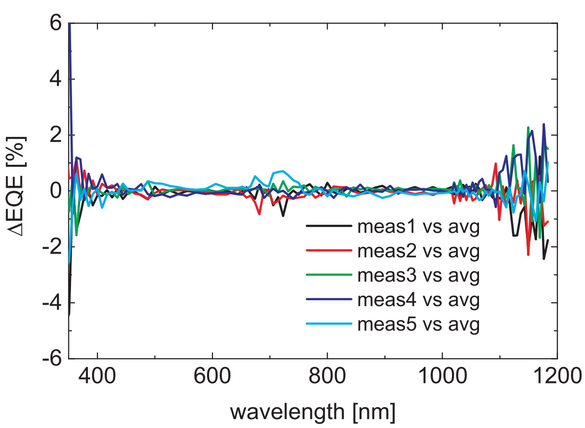

Fig. 6. The relative difference between the EQE spectra obtained from five FOMS measurements on the n-PERT solar cell described in Fig. 5 with respect to the average of the five measurements.

of the calibration cell in those parts of the spectrum, despite the fact that both the reference cell and the device under test have a lower response there.

Apart from the high accuracy, also the repeatability of the FOMS measurement is extremely high, which is illustrated by the very small relative EQE differences between five measurements on the same solar cell when considering $\Delta EQE = (EQE_{measX} - EQE_{avg}) / EQE_{avg} \cdot 100\%$, as is shown in Fig. 6. Such a high repeatability is not only the consequence of the powerful modulation scheme, but it also shows that the result can be resolved with extremely high precision thanks to the Fourier transform and the short measurement time of 1–10 s. This short measurement time implies that there is a negligible difference in the spectrum of the probe light between the measurement of the reference cell and the device under test, which is certainly not a guarantee in monochromatic EQE measurements, where these two measurements are typically taken several minutes apart. This time delay between the reference and device under test measurements becomes more important when the spectrum of the light source has not been properly stabilized before conducting reference or device under test measurements or when the power supply of the light source is not sufficiently stable. Additionally, a monochromator cannot be set to exactly the same position at all times, which is especially problematic when using arc lamps, thus illustrating the need for regularly recurring reference measurements in a conventional EQE system. When avoiding the use of a monochromator, as is done in the FOMS, this concern with respect to reference measurements is no longer an issue.

4. Conclusions and outlook

Accurate, highly repeatable, and ultrafast measurements of the EQE spectrum on a c-Si solar cell have been demonstrated by the Fast Optical Measurement System both on a-Si:H and c-Si solar cells using a DMD and a light modulation scheme inspired on a Michelson interferometer. With respect to conventional monochromatic measurements we have achieved a reduction in measurement time of three orders of magnitude without compromising on the accuracy of the final measurement result. To further showcase the strength of the FOMS we aim to proceed with similar EQE validation measurements on other types of c-Si solar cells (both homojunctions and heterojunctions), as well as other PV technologies such as organic/perovskite, copper indium gallium selenide (CIGS), and thin-film silicon (TF-Si), as well as hybrid combinations of different PV technologies into multi-junction devices. To enable measurements on multi-junction solar cells we strive to implement bias lighting into the system, which will also make it possible to imitate typical outdoor illumination conditions with a white light bias (~0.4 sun) and that moreover enables measurements of c-Si solar cells at typical carrier injection levels. Finally, when the reflectance/transmittance stage is also included, ultrafast measurements of the internal quantum efficiency (IQE) will become possible as well while measuring the EQE and reflectance in exactly the same position on the solar cell.

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