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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 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.

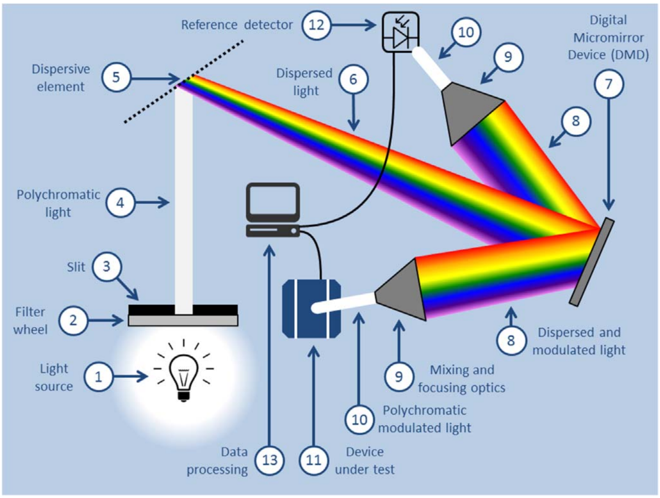

Fig. 1. Schematic layout of the Fast Optical Measurement System in which the light from a source (1) is first directed through a filter wheel (2) and a slit (3). The polychromatic light (4) then illuminates a dispersive element (5), which creates a dispersed light beam (6). This beam illuminates the 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).

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