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Citation: Review of Scientific Instruments **88**, 086112 (2017); doi: 10.1063/1.5000057
View online: http://dx.doi.org/10.1063/1.5000057
View Table of Contents: http://aip.scitation.org/toc/rsi/88/8
Published by the American Institute of Physics

REVIEW OF SCIENTIFIC INSTRUMENTS **88**, 086112 (2017)

Note: Modification of an FTIR spectrometer for optoelectronic characterizations

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(Received 28 March 2017; accepted 13 August 2017; published online 25 August 2017)

We propose a very simple system to be adapted to a Fourier Transform Infra-Red (FTIR) spectrometer with which three different types of characterizations can be done: the Fourier transform photocurrent spectroscopy, the recording of reflection-transmission spectra of thin film semiconductors, and the acquisition of spectral responses of solar cells. In addition to gather three techniques into a single apparatus, this FTIR-based system also significantly reduces the recording time and largely improves the resolution of the measured spectra compared to standard equipments. *Published by AIP Publishing.* [http://dx.doi.org/10.1063/1.5000057]

Optoelectronic characterizations of thin film semiconductors and devices for photovoltaic applications are still a matter of research for materials and conversion efficiency optimization. Among these techniques, we can quote the Fourier Transform Photocurrent spectroscopy (FTPS) first proposed by Poruba *et al.*[1,2] and largely detailed since then.[3] FTPS was developed to replace the Constant Photocurrent Method (CPM) proposed earlier by Vaněček *et al.*[4] The great advantages of FTPS over CPM are the speed and high resolution at which the same spectroscopy can be achieved. These advantages are due to the fact that all the wavelengths are present at the same time in the Fourier Transform Infra-Red (FTIR) light, the respective sample response to each wavelength being analyzed by applying an inverse fast Fourier transform to the sample signal to eventually obtain the complete spectrum. The use of an FTIR spectrometer as a light source for the analysis of sample responses was also proposed by Tomm *et al.*[5] to study the aging of high power light emitting devices (LEDs). Earlier, Hennies *et al.*[6] had proposed to build a Fourier transform spectrometer specially dedicated to the study of spectral responses of solar devices. All these experiments suggest that the principles of an FTIR spectrometer could be used in many cases as soon as a one seeks to measure a "spectral response" of a material or a device. In this note, we describe a very simple system to be adapted to a standard FTIR spectrometer to perform FTPS, fast reflection-transmission (R/T) measurements, and fast spectral response (SR) measurements of photovoltaic devices, gathering in a single bench three different experiments that are usually performed with three different apparatus.

Detailed descriptions of different setups for FTPS can be found in Refs. 2 and 3. These setups have the major drawback to be very rigid since the positions of the sample and optical components are fixed. To be more versatile, we propose the setup described in Fig. 1 that allows three types of characterization with almost no modifications of the system.

For this setup, we have used a Nicolet IS50R FTIR spectrometer from Thermo Scientific. To work in the visible part of the light, the light source is a halogen lamp, all the mirrors are covered with aluminum, and the beam splitter of the Michelson interferometer is a quartz plate. With such a system, we easily cover a range of wavelengths from 390 nm to 1800 nm. The beam of light exiting the Michelson interferometer, 2.4 cm in diameter, and focused in the standard FTIR spectrometer to the film position in the sample compartment, is even more focused by a silica lens, 5 cm in diameter and approximately 5 cm of focal length ($f/1$), onto the input of one of the two branches of a bifurcated optical fiber bundle from Newport Corp. (input diameter 3.2 mm, numerical aperture NA = 0.22). This branch of the optical fiber bundle was fixed onto an XYZ mount to optimize the collection of the light coming out of the FTIR spectrometer. A filter wheel is set in between the lens and the optical fiber entrance to select appropriate wavelength ranges if needed. In this way, the light of the FTIR spectrometer can be easily shone onto a sample or photodiode set close and perpendicular to the common output of the fiber bundle (output diameter 4.7 mm, NA = 0.22). The system we have designed to collect the light of the FTIR spectrometer is compact and can be easily inserted into the sample compartment of the FTIR as shown in Fig. 2.

In all the experiments, the responses of the samples or photodiodes to the FTIR illumination have to be amplified. We chose a low noise, broadband, and high gain current/voltage converter, DLPCA200 from FEMTO. With a mirror velocity of 0.158 cm/s and a data spacing of 3.58 cm^{-1}, each spectrum is recorded in 1 s with a high resolution, 5500 data points between 390 and 1750 nm, and a maximum modulation frequency of 8 kHz at 390 nm, much lower than the bandwidth of DLPCA200 (50 kHz at a gain of 10^7). The signal is subsequently injected in an external input of the FTIR (see Fig. 1) to be treated by fast Fourier transform to obtain the final spectrum.

For the FTPS experiment, the sample is a thin film deposited on glass and fitted with two ohmic and parallel electrodes (1 cm height, 2 mm apart). It is fixed onto an electronic

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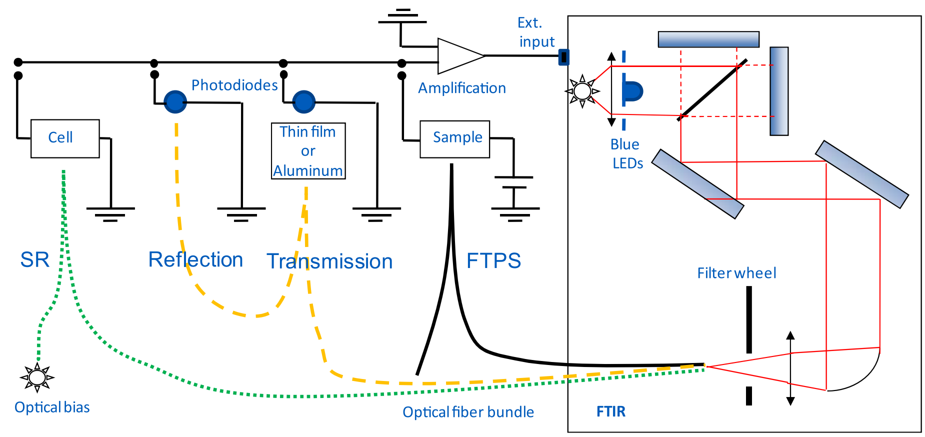

FIG. 1. Schematic of the setup designed to illuminate the sample with the light coming from the Michelson interferometer of an FTIR spectrometer. The *same* optical fiber bundle can be used to perform FTPS acquisition (black full line), reflection-transmission measurements (yellow dashed line), and spectral response (green dotted line) with a minimum of modification of the system holding the sample to be studied.

circuit plate by two springs that both maintain the sample in position and play the role of electrical connections. BNC cables allow the connection to the amplifier and to a bias source. A very thin hole, of 0.8 mm width and 5 mm height, was drilled through the substrate holder behind the sample to let the light pass through it and to deduce the transmittance of the film by placing a photodiode just behind the sample. Two types of photodiodes are used: a crystalline silicon (c-Si) one for the range 390–1100 nm and an InGaAs one for the range 800–1750 nm. The variations of the absorption coefficient vs photon energy, $\alpha(h\nu)$, can be deduced from the FTPS spectra and the transmittance spectra, measured at the same position of the sample, following the procedure proposed by Vaněček *et al.* for the "absolute" CPM.[7]

The same transmittance measurement can be performed on a thin film without electrodes. Besides, the fiber bundle being bifurcated, the light reflected by the film enters back into the fiber and can be measured at the output of the other branch by means of the photodiodes at our disposal. For the reflectance measurement, the flux of incident light can be estimated by replacing the sample by an aluminum mirror and taking into account the aluminum reflectance to correct the measured spectrum. From these R/T measurements, one can deduce some parameters of the film such as the index, thickness, and $\alpha(h\nu)$ in the high photon energy region using the theoretical developments proposed by Poruba *et al.*[8] The measured $\alpha(h\nu)$ can also be used to set the FTPS curves to their absolute value if needed.

For both the FTPS and R/T measurements, the final spectra are the average of 30–40 acquisitions to improve the signal to noise ratio. However, the acquisition time of all the spectra for the FTPS or R/T study does not exceed a few minutes (5 to 8 min).

To measure the SR in a single shot, we can modify the light source of the FTIR by inserting in the beam, before the interferometer (see Fig. 1), a plate in which we have fixed 5 blue LEDs surrounded by two semi-circular apertures to let a part of the halogen light pass through it [see Fig. 3(a)]. These

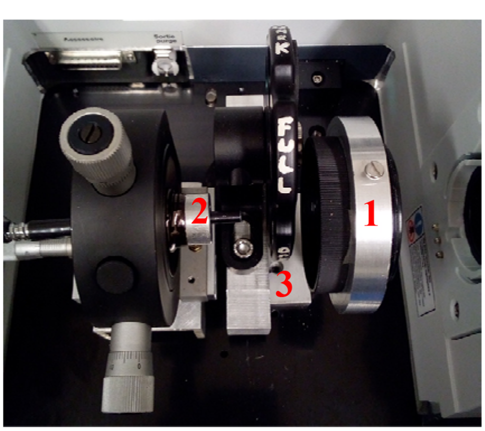

FIG. 2. System designed to collect the light from the Michelson interferometer of the FTIR: (1) a silica lens concentrating the light on the entrance of one leg of a bifurcated optical fiber bundle (2) and a filter wheel in between to select different ranges of wavelengths (3).

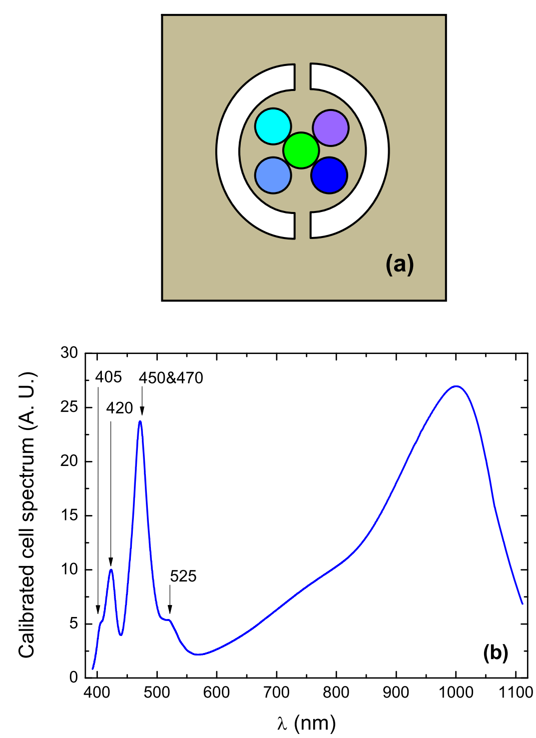

FIG. 3. (a) Design of the LEDs and semicircular apertures set in an electronic plate to enhance the light emission of the source in the range 390–550 nm and (b) spectrum of the modified light source measured with a calibrated c-Si photodiode. The wavelengths corresponding to the LED emission peaks are indicated in the figure in nm.

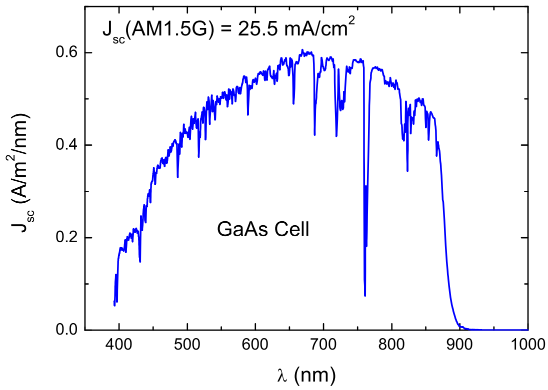

FIG. 4. Spectrum of the short circuit photocurrent density that would flow in a GaAs cell under AM1.5G illumination. The integral of this curve gives a short circuit photocurrent density of 25.5 mA/cm^2.

blue LEDs compensate the weak emission of the halogen lamp in the blue region of its spectrum, a region where the responses of the cells are also often weak. An example of the spectrum of this modified light source is presented in Fig. 3(b). Without these blue LEDs, the SR appears very noisy in the blue region of the spectrum. To determine the cell SR, the output of the fiber has to be set close to it so that all the light exiting the fiber is shone onto the device when measuring the current spectrum. The incident power is deduced from the same type of measurement performed on a large area c-Si photodiode, the SR of which is calibrated. From the SR, one can deduce the external quantum efficiency and the short circuit current density under AM1.5G power density [W/(m^2/nm)], $J_{sc}(\lambda)$ = SR × AM1.5G. An example of a $J_{sc}(\lambda)$ spectrum for a GaAs cell is shown in Fig. 4. The total short circuit current density is J_{sc}(AM1.5G) = 25.5 mA/cm^2, in good agreement with the value provided by the fabricant (24.9 mA/cm^2).

The SR measurements are usually done with an excellent signal to noise ratio (>100) even when one records a single spectrum. The spikes in the curve of Fig. 4 do not reveal any noise problem but come from the spikes of the sun AM1.5G spectrum, these latter resulting mainly from absorption from molecules of the atmosphere. This behavior underlines the excellent resolution with which the acquisition is done. Since a single spectrum can be recorded within 1 s, it opens the possibility to achieve a mapping of large area cells, up to 15.6 × 15.6 cm^2, with the resolution of the output of the optical fiber (∼5 mm) within a "reasonable" acquisition time. The last advantage of our system is that it is possible to add an optical bias on the other branch of the optical fiber when studying tandem cells (see Fig. 1).

As a conclusion, we have designed a very simple system to be inserted into the sample compartment of an FTIR spectrometer to collect the light at the exit of the Michelson interferometer. With this system, it is possible to perform three types of optoelectronic characterizations of thin film semiconductors and solar devices with a single apparatus: FTPS, acquisition of R/T spectra on thin films, and SR measurements of solar cells. These acquisitions are fast and with an excellent resolution giving the opportunity to achieve systematic evaluations of some of the properties of a thin film material. Indeed, it takes between 10 and 15 min of acquisition to obtain a rather complete overview of a particular thin film material potentialities by performing characterizations on the thin film alone (FTPS and R/T) and when incorporated as an absorber in a solar device (SR). It is therefore easy and fast to achieve a comparative study of several thin film materials with one particular characterization technique, or the three of them, for optimization of the deposition parameters to improve the device conversion efficiency. In terms of future developments, the setup we designed also offers the possibilities to study tandem cell performances as well as to achieve mappings of large area cells to check their homogeneity within a reasonable time of acquisition. Finally, the system we presented is easy to use and no special training is required except mastering the operating procedure of the FTIR. It could be then developed in any laboratory working in the photovoltaic domain, seeking for ready-to-use characterization techniques and in which an FTIR apparatus is available.

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