An automated experiment for determination of thin film semiconductor transport parameters

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Abstract: Thin film semiconductors are more and more the major components of solar devices. Nevertheless, these materials are still the subjects of intense research to improve their properties and reach better cell efficiency. Many experiments have been dedicated to the study of their opto-electronic parameters, most of them using the photoconductivity property of these films. The different techniques use several flux spatial and temporal ‘shapes’, the light impinging on the sample being uniform or with interferences, steady, modulated or chopped. This is why these different techniques are usually performed with different benches and the state of the sample may change from one bench to the other. In this communication we show that the light ‘shape’ can be tailored for the needs of several techniques by means of an electro-optic modulator. Therefore, these techniques can be gathered on the same bench, the samples being subsequently studied under the same conditions of vacuum and temperature. We shall show how we have achieved an ‘all-in-one’ bench and present some experimental results to illustrate all the possibilities of this new bench.

1. Introduction
Thin film materials (Hydrogenated amorphous silicon (a-Si:H), CIGS, Sb2S3, organic polymers,...) are more and more integrated into solar energy conversion devices. For this reason, lots of research has been carried out for measuring their transport parameters so as to optimize the deposition conditions and their properties. Some of them (e.g. a-Si:H, CIGS) are currently integrated into solar modules whereas others are still under intensive research for future applications. Several techniques developed to determine thin films transport parameters are based on their photoconductivity property, and only the light excitation spatial and temporal ‘shape’ is varied from one experiment to the other.

Considering a subset of experiments in which the photon energy is such that both type of carriers are generated, we can quote the following methods. The simplest one is the steady-state photoconductivity (SSPC) in which one records the evolution of the film photoconductivity with temperature and/or generation rate. More sophisticated techniques were designed such as the transient photocurrent (TPC) technique [1, 2] in which, after shining a short light pulse onto the film, the transient current is recorded over decades of time. In the frequency domain the modulated photocurrent (MPC) technique was proposed by H. Oheda [3]. Other experiments are based on illuminating the film with a light grating created by two interfering laser beams. The grating can be fixed as in the steady state photocarrier grating (SSPG) [4], can move at a constant velocity along the film as in the moving grating technique (MGT) [5], can be modulated at a given frequency like in the modulated photocarrier grating (MPG) [6] technique, or is oscillating on top of the sample as in the Oscillating Photocarrier grating (OPG) technique [7].
Each of these techniques brings some insight into the transport parameters and/or density of states (DOS) of the studied thin film. One of the main issues is that they are usually performed on different benches. Therefore, the state of the studied sample may vary from one bench to the other. For instance some experiments are performed under vacuum at different temperatures whereas others are usually achieved at room temperature in the air, not to speak of the time that elapses in between two experiments for which the sample can evolve if left in the air as for organic thin films. The ideal bench would be an all-in-one bench on which most of these experiments can be carried out under the same conditions but the different intensities and temporal and spatial shapes of the light used for each of them make this task more difficult.

In this communication we show that at least some of them can be automated and gathered onto a single bench, the light being shaped by means of an electro-optic modulator (EOM). We first present shortly the main experiments that can be gathered on a single bench. Then we shall show how an EOM can be set to properly shape the light and, finally, we shall show some experimental results obtained on a-Si:H and bulk hetero-junction polymer illustrating the versatility of this new bench.

2. Experiments

All the samples studied by the experiments described in the following are built in coplanar geometry, the thin films being deposited on an insulating substrate and fitted on top by two parallel and ohmic electrodes between which a bias is applied.

The SSPC technique is one of the most widely used experiments. From the study of the evolution of the current in the dark, the activation energy of the conductivity and the energy position of the dark Fermi level can be estimated. With light shone onto the sample at different fluxes it is possible to deduce the evolution of the photoconductivity with temperature and flux as well as the mobility lifetime products of the majority carriers ($\mu \tau_{\text{maj}}$).

The SSPG technique was first proposed by D. Ritter et al. [4]. It is one of the few experiments from which an ambipolar diffusion length $L$ can be measured that turns out to be that of the minority carriers if their mobility lifetime product ($\mu \tau_{\text{min}}$) is much smaller than that of majority carriers ($\mu \tau_{\text{maj}}$). For more details on this technique the reader may have a look at the review by R. Brüggemann [8]. The basic idea is to illuminate the sample with an interference array that generates two arrays of space charge in the sample. These two arrays might disappear by ambipolar diffusion, each array interacting with the other due to their opposite charge. If it is not the case, for instance if one of the carriers is particularly slow, an internal field array appears that alters the majority carrier current originating from the applied external bias. The interference array is achieved by splitting a laser beam into two beams that are subsequently directed onto the sample making an angle $\theta$ between them. One of the beams, the probe beam, is attenuated by a factor of say 30 after the beam splitter whereas the other one, the main beam, is not attenuated and fixes the equilibrium state of the sample. If the polarization of the light of both beams is parallel to the electrodes, interference fringes are created with a grating period $\Lambda$ depending on $\theta$, whereas if the polarization of the light of one beam is set perpendicular to the electrodes the two beams simply superimpose onto the sample. Measurements of the evolution of the ratio $\beta$ of the current with interferences $I_{\text{wl}}$ over the current without interferences $I_{\text{woi}}$ with the grating period $\Lambda$ allows the deduction of the diffusion length. These two currents are those due to the probe beam contribution and, to get an accurate measurement, this beam is chopped at a frequency of a few tens or so Hz and the currents are recorded by a lock-in amplifier. Ritter et al. have shown that

$$\beta(\Lambda) = \frac{I_{\text{wl}}}{I_{\text{woi}}} = 1 - \frac{2\phi}{1 + (2\pi\Lambda/L)^2}$$

and a fit of $\beta(\Lambda)$ gives the two parameters $L$ and $\phi$ [4]. This latter parameter has only little interest and its value, always lower than one, depends on the contrast of the interference fringes, the dependence of the current with the generation rate and the ratio between the currents in the dark and under illumination. The knowledge of $L$ is more interesting for, if they are not swept out by drift and diffusion, the slowest carriers will accumulate in a solar device and create a space charge limiting the
cell efficiency. This is why the flux of the main beam must be as high as possible to be close to sun illumination in order to get an estimate of \(L\) close to that found in an operating solar device.

The MPC technique was first proposed by H. Oheda [3] and the data treatment was improved by R. Brüggemann et al. [9]. The basic idea is to illuminate the sample with a DC flux to which a small modulation at an angular frequency \(\omega\) is added, and to record the amplitude \(|\sigma_\omega|\) and phase lag \(\varphi\) with respect to the alternating generation rate \(G_{ac}\) of the resulting alternating conductivity by means of a lock-in amplifier. It was shown [9, 10] that the amplitude and phase lag were due to interactions of the majority carriers with the density of localized states in the gap (DOS) and that it was possible to deduce the variations with energy of the quantity \(NC/\mu\), called MPC-DOS in the following, \(N\) being the density of states at an energy \(E\), \(\mu\) the extended states mobility and \(C\) the capture coefficient of the states trapping free majority carriers, from the equations

\[
\frac{N(E_\omega)C}{\mu} = \frac{2}{\pi k_B T} q G_{ac} \sin \varphi \left| \sigma_{ac} \right|, \tag{2}
\]

with

\[
E_\omega - E_{be} = k_B T \ln \left( \frac{CN_{be}}{\omega} \right), \tag{3}
\]

in which \(q\) is the absolute value of the electronic charge, \(T\) is the temperature, \(k_B\) the Boltzmann constant, and \(N_{be}\) the equivalent density of states at the band edge located at \(E_{be}\). It can be seen that all the quantities on the right hand side of equation (2) are known. Therefore, by varying experimentally \(T\) and \(\omega\) equations. (2)-(3) offer the possibility to scan the DOS of the material provided \(C, \mu\) and \(N_{be}\) are known. One quantity of particular importance is the attempt to escape frequency \(\nu = CN_{be}\) for it fixes the energy scale of the DOS spectroscopy (see equation (3)). Experimentally, to reach a large range of energy, the \(NC/\mu\) spectroscopy is achieved at different temperatures with different angular frequencies. Typically, the temperature can be varied between 120 K and 450 K in 20 K steps and the frequencies range from 12 Hz to 40 kHz.

To achieve the three experiments briefly described above, one can see that we need a coherent light source, such as a laser, to create the interference pattern on the sample. Besides only a laser can provide enough flux to perform the SSPG technique with a flux as close as possible to solar illumination. However, this light must be shaped to fulfil the requirements of each technique. For the SSPC technique the flux must be constant and even adjustable to reach different values, for the SSPG technique one beam must be chopped at a low frequency and for the MPC technique the light is the addition of a DC flux, preferably adjustable, and of an AC one, adjustable too, the frequency of which should vary over several decades of frequencies. Hence, a system that can be tuned to provide all these illumination ‘shapes’ so as to gather the three experiments on a single bench is needed.

3. Experimental set-up

3.1 The EOM plus polarizer system

In a Pockels cell as in an EOM, containing for instance an ADP crystal, the phase shift \(\psi\) of the light can be modified according to the polarisation \(U\) applied to the crystal. In the following, we assume that the light entering the EOM is vertically polarized and, with \(U = U_m\) it goes through the EOM with no modification. On the other hand if \(U = 0\) then the exiting light is horizontally polarized.

Figure 1 explains the different axes of the system: X’ and Y’ are the axes of the crystal (fast and slow respectively) whereas X and Y are just the axes indicating the horizontal and vertical directions respectively. Figure 1 also explains how the EOM must be fitted on the bench to satisfy the requirements of all the experiments to be achieved, i.e. tilted 45° with respect to the vertical. We call \(E_Y\) the amplitude of the light entering the EOM. With \(U=0\) the coordinates of the electric field of the vertically polarized light entering and exiting the EOM can be written on the axes X’Y’.
where $\Omega$ is the pulsation of the light and $t'$ the time. If a bias $U$ is applied to the crystal the field of the light at the exit of the EOM transforms into

$$
\vec{E}_{xy} = \begin{bmatrix}
\frac{E_M}{\sqrt{2}} \cos(\Omega t') \\
\frac{E_M}{\sqrt{2}} \cos(\Omega t' + \psi)
\end{bmatrix},
$$

an expression that can be re written in the XY axes after some easy calculation

$$
\vec{E}_{xy} = \begin{bmatrix}
E_M \sin \left( \frac{\psi}{2} \right) \sin \left( \Omega t' + \frac{\psi}{2} \right) \\
E_M \cos \left( \frac{\psi}{2} \right) \cos \left( \Omega t' + \frac{\psi}{2} \right)
\end{bmatrix}
$$

![Figure 1. The different axes to be considered in the system.](image)

Practically, the EOM and EOM driver are tuned with the following procedure. A polarizer is set at the output of the EOM, letting go through it only vertically polarized light, and the voltage of the EOM driver is fixed at a very low value $U_{\text{min}}$ that we shall take to be equal to zero in the following. The EOM is adjusted, tilted etc. so that the amplitude of the light after the polarizer is minimum, indicating that the light exiting the EOM is horizontally polarized. Then, the polarizer is rotated $90^\circ$, in a way such that only the horizontally polarized light can go through it and the voltage of the EOM driver is increased up to $U_{\text{max}}$ for which the amplitude of the light going through the system EOM+polarizer is minimum again. This means that the light at the output of the EOM is vertically polarized. If we come back to the expression of the light electric field, see equation (6), it means that for $U = U_{\text{min}} = 0$ then $\psi = \pi$ and for $U = U_{\text{max}} \psi = 0$, and we can deduce an expression of $\psi$ versus $U$

$$
\psi = \pi \frac{U_{\text{max}} - U}{U_{\text{max}}},
$$

The EOM driver is connected to a function generator and the final expression of $U$ applied to the crystal is

$$
U = U_{\text{max}}/2 + V_0 + V \sin(\omega t)
$$
the $U_{\text{max}}/2$ being fixed by the user on the EOM driver and the $V_0 + V \sin(\omega t)$ being added by the function generator after amplification. An expression of $\psi$ is therefore

$$\psi = \frac{\pi}{2} - \frac{V_0 + V \sin(\omega t)}{U_{\text{max}}}. \quad (9)$$

If we assume that the polarizer is vertically positioned, letting out only the vertical component of the light electric field, we can calculate the intensity $I$ of the light reaching the sample writing

$$E_y = \Re\{E_i\} = \Re\{E_{i'}/2 \exp(j\omega t)'[1 + \exp(j\psi)]\}. \quad (10)$$

The intensity will be $I = \frac{1}{2} E_i E_{i'}^*$ and we end with

$$I = \frac{E_{i'}^2}{4} [1 + \cos(\psi)] = \frac{E_{i'}^2}{4} \left[1 + \sin\left(\frac{\pi}{2} \frac{V_0 + V \sin(\omega t)}{U_{\text{max}}} \right)\right]. \quad (11)$$

Equation (11) describes the different possibilities of flux ‘shaping’ by means of the EOM+polarizer system. The DC flux entering the system can be attenuated, modulated or chopped. This is illustrated in figure 2. Taking $E_{i'} = \sqrt{2}$ and assuming that $U_{\text{max}}$ is reached for 2.6 V, the choice of couples of $(V_0, V)$, applied to the EOM driver, as $(1.1 \text{ V, } 0 \text{ V}), (0.9 \text{ V, } 0.12 \text{ V}), (0 \text{ V, } 1.3 \text{ V})$ gives an output flux either continuous but attenuated (diamonds), modulated (squares) or chopped (circles), respectively.

![Figure 2](image_url)

**Figure 2.** Intensity as function of time at the output of a system EOM+polarizer for different voltages applied to the EOM driver.

This means that the system EOM+polarizer can be used to tailor the flux impinging the sample either continuous for SSPC, modulated for MPC or chopped for SSPG, with the possibility in these two last cases to adjust the angular frequency $\omega$ of the flux variations. It can be noted that the same tailoring is possible if the polarizer is rotated 90° to let the horizontally polarized light to go through it. This just adds a phase shift of 180° to the curves displayed in figure 2 without modifying the amplitudes.

### 3.2 The experimental bench

Figure 3 shows a schema of the whole bench. The light source is a HeNe laser ($\lambda = 633$ nm) and the beam at its exit goes through two polarizers. The second one fixes the polarization of the light perpendicular to the plane of the figure and the global intensity of the light can be adjusted by rotating the first one. The beam is subsequently split into two equivalent beams. One, the probe beam, is attenuated and goes through the EOM+polarizer system and a second one, the main beam, is reflected toward a mobile mirror. The SSPG technique has been automated by means of a mobile mirror reflecting the main beam onto a series of nine return mirrors. Changing the choice of the return mirror changes the angle in between the two beams and therefore the grating period as depicted in the figure.
By means of the nine mirrors the grating period can be varied between 1 µm and 24 µm. For more
details on this automated SSPG system see [11]. For the other experiments, SSPC and MPC, the
mobile mirror is set in front of the first return mirror and a filter wheel can be rotated so as to select
the illumination impinging on the sample. The two beams can be used, either at full or attenuated flux, or
only one of the two beams, or even none of them (dark position) by rotating the filter wheel fitted with
different neutral density filters to the suitable configuration. All the movements of the mobile mirror,
rotating polarizer, and filter wheel, are computer controlled and the different configurations for SSPC,
SSPG and MPC can be set one after the other automatically. The sample is fitted onto the cold finger
of a cryostat, one electrode connected to a voltage source and the other one to a computer controlled
switch to record the signal either on an electrometer (SSPC) or on a lock-in amplifier (SSPG, MPC).
All these experiments can be thus performed at different temperatures under different conditions of
flux keeping the sample in the cryostat at the same position which ensures the same state of the film
for all the experiments performed one after the other.

Figure 3. Schema of the experimental bench, using the EOM+polarizer system, with which SSPC,
SSPG and MPC experiments can be achieved. The sample is set in a cryostat not shown here.

4. Experimental results

4.1 Hydrogenated amorphous silicon

Hydrogenated amorphous silicon (a-Si:H) was widely studied to improve its transport properties
before being incorporated into solar devices and all the experiments quoted above have been applied to
this material. It is not the purpose of this paper to make a review of the a-Si:H studies and some
theoretical developments and basic properties of a-Si:H thin films can be found in [12-16]. We shall
briefly recall orders of magnitude of the main transport parameters found for ‘standard’ a-Si:H. This
material, though intrinsic, is slightly n-type with an activation energy in the range of 0.6-0.8 eV. The
extended states electron mobility has values in the range of 10-40 cm²V⁻¹s⁻¹ [14, 15]. The mobility-
lifetime product for electrons and holes at room temperature are usually in the ranges of 5×10⁻⁸-5×10⁻⁶
cm²V⁻¹, and 1×10⁻⁸-1×10⁻⁸ cm²V⁻¹, respectively, both depending on the flux and on the quality of the
films [8, 12]. The capture coefficient of the conduction band tail states is of the order of 10⁻⁸ cm⁻³s⁻¹
leading to an attempt to escape frequency of the order of 5×10¹¹ s⁻¹ [14, 16].

A 0.5 µm thick a-Si:H film was deposited onto a glass substrate by radio-frequency (13.56 MHz)
powered plasma enhanced chemical vapour deposition with a power of 30 W, the silane being diluted
in hydrogen (10%, 90%) at a total pressure of 2 Torr and a temperature of 190 °C. Two silver paste
ohmic electrodes 1 mm apart were set on top of it. The dark conductivity and SSPC were measured
each 10 K in the range 120-440 K with two different fluxes (2×10¹⁵ and 6×10¹⁶ cm⁻²s⁻¹). The SSPG
was measured each 20 K in the same range of temperature with a flux of 6×10¹⁶ cm⁻²s⁻¹, the maximum
flux at our disposal. The MPC spectra were recorded each 20 K in the range 110-400 K. For this last experiment the DC and AC fluxes were $8 \times 10^{14}$ and $2 \times 10^{14}$ cm$^{-2}$s$^{-1}$, respectively, and the frequencies were in the range 12 Hz-27 kHz.

Figure 4. Results obtained on an a-Si:H thin film. (a) SSPG $\beta(A)$ curve obtained at 300 K, (b) Arrhenius plots of the dark and photo currents measured with two fluxes shown in the figure, (c) Arrhenius plots of the mobility lifetime products of the minority ($\mu\tau_{\text{min}}$) and majority carriers ($\mu\tau_{\text{maj}}$) for different fluxes, (d) MPC-DOS spectroscopy; the attempt-to-escape frequency was chosen equal to $10^{12}$ s$^{-1}$ to fix the energy scale and the measurement temperatures are displayed in the figure.

We present in figure 4 several results obtained with the automated experiment described above. Figure 4a shows a curve $\beta(A)$ obtained by SSPG performed at 300 K. The diffusion length we deduce from the fitting of the $\beta(A)$ curve is of the order of 130 nm, a typical value for a-Si:H. Figure 4b displays an Arrhenius plot of the variations of the dark current (diamonds) and of two photocurrents measured respectively with fluxes of $2 \times 10^{15}$ cm$^{-2}$s$^{-1}$ (squares) and $6 \times 10^{16}$ cm$^{-2}$s$^{-1}$ (circles). The activation energy, $E_a = 0.67$ eV, deduced from the measurements in the dark, is again typical of a-Si:H. The saturation of the dark current at $10^{-13}$ A at low temperatures is due to the limitation of the sensitivity of the electrometer. From the SSPG and SSPC measurements we deduce the evolution with temperature of the mobility-lifetime product of the majority carriers, in this case the electrons ($\mu\tau_{\text{maj}}$), and of the minority carriers, here the holes ($\mu\tau_{\text{min}}$). Indeed, the ambipolar $\mu\tau$ deduced from SSPG is much smaller than that of the electrons and can be attributed without ambiguity to the minority carriers. The results are displayed in figure 4c. The saturation of the $\mu\tau_{\text{min}}$ values observed at low temperatures is probably due to the limitation of the experiment when dealing with very low $L$, i.e. lower than 50 nm [11]. Finally, in figure 4d we present the density of states (DOS) above the Fermi level deduced from MPC measurements. One can observe a ‘classical’ DOS made of a conduction band tail and deep states. Each spectrum displayed by a symbol was recorded at a given temperature and each symbol in a spectrum corresponds to a given frequency. The envelope of all the spectra describes the DOS. It must be recalled that the value of $NC/\mu$ is known from all the experimental
quantities appearing on the right hand side of equation (2). To fix the energy scale the value of the attempt-to-escape frequency was chosen equal to $\nu = 10^{12} \text{s}^{-1}$ according to previous results [14, 16]. This value is that of the conduction band tail states and is probably different for the deep states. It is also for this value that the different band tail MPC spectra obtained at different temperatures present the best match one with the other. This property can be used to estimate the attempt-to-escape frequency for materials less studied than a-Si:H and for which $\nu$ is unknown.

4.2 Organic polymers

During the last decade bulk hetero-junction (BHJ) polymers have received a considerable attention and conversion efficiencies of solar cells larger than 12 % have been reached. In addition, the stability of the cells has been largely improved [17]. However, only few experiments dedicated to the study of transport parameters have been applied to these materials. The transport properties have been mainly studied with time-of-flight experiments and models of density of states have been proposed to explain the peculiar behavior of the drift mobility with the applied field [18, 19]. More recently photoconductivity experiments have been applied to BHJ thin films by R. A. Street et al. [20, 21] from the results of which a model of DOS has been derived. In addition, these authors have shown that the carrier transport could occur following a multiple trapping process as in disordered inorganic materials (e.g. a-Si:H). Therefore, the global picture describing transport processes in organic semiconductors seems very similar to that describing transport in disordered inorganic films, and, since the techniques described in this communication were successfully applied to a-Si:H, we have also tried to apply them to P3HT:PCBM thin films [22]. We are aware that the carrier generation is different (excitons instead of band to band) but in both cases electrons are generated in one material and in one band (Lowest Unoccupied Molecular Orbital) and holes in another material and another band (Highest Occupied Molecular Orbital) as in inorganic semiconductors (conduction and valence band respectively). In addition, the notion of majority and minority carrier may be slightly different in organic semiconductors than the one currently used in inorganic ones, especially the doped ones. However, as in intrinsic inorganic semiconductors (e.g. a-Si:H), a type of carrier may dominate the current because these carriers are more numerous and/or more mobile. By extension we shall still use the terms ‘majority’ and ‘minority’ carriers in the following.

The films were prepared from a mixture of powders of P3HT and PCBM in a ratio of 1:1 in weight. This mixture was dissolved in dichlorobenzene and spin-coated onto a glass substrate at a speed of 500 or 700 rpm to give a thickness of the order of 200 nm. After annealing at a temperature of 75 °C during 30 min the samples were fitted with two parallel aluminium electrodes, 0.5 mm apart, that revealed to be ohmic up to 30 V applied. All the experiments have been performed with 20 V applied. The samples were kept under vacuum ($10^{-5}$ Torr) before and during measurements to avoid any contamination.

The measurements were performed in the range 120 K-380 K each 10 K for the SSPC technique under the same fluxes as for a-Si:H. For the SSPG and the MPC techniques, data were recorded only each 20 K. The SSPG technique was achieved with a flux of $6 \times 10^{16} \text{cm}^{-2}\text{s}^{-1}$. The MPC technique was achieved with a DC flux of $2 \times 10^{15} \text{cm}^{-2}\text{s}^{-1}$ and an AC flux four times lower. The frequencies of the modulation were varied in the range 12 Hz-8 kHz.

Among all the films tested, one, prepared at 500 rpm, exhibited very promising transport properties with a large diffusion length. The results of the different experiments are exemplified in figure 5. Figure 5a displays the variation of $\beta$ vs $A$ obtained at 280 K with the SSPG experiment. The symbols are the data points and the line is the fit to the data using equation (1). The agreement between both is excellent and we found $L = 160$ nm. In figure 5b we present the Arrhenius plots of the dark current and of two photocurrents measured with two different fluxes. From the variations of the dark current we deduced an activation energy of 0.26 eV, though it is still questionable whether this value reflects the Fermi level position in BHJ materials or not, since the mobility could be slightly activated [18].

Figure 5c displays the Arrhenius plot of the mobility-lifetime products of the minority ($\mu \tau_{\text{min}}$) and majority carriers ($\mu \tau_{\text{maj}}$) for different fluxes. It can be seen that the $\mu \tau$ deduced from the ambipolar diffusion length are much smaller than the $\mu \tau_{\text{maj}}$. This is why we have assumed that these $\mu \tau$ were
those of the minority carriers. The reader may note also the limited range of temperature in which we have deduced $\mu \tau_{\text{min}}$ values. Though the SSPG measurements were performed on a large range of temperature, an analysis of the data by a method proposed by Balberg et al. has shown that the SSPG measurements below 220 K were not reliable [23]. The variations of $\mu \tau_{\text{min}}$ seem to be activated but this behavior could be a consequence of the limited range of temperature of this data. An activation could have been found also for $\mu \tau_{\text{maj}}$ if the temperature range had been limited to 160-260 K. More work is needed to understand these behaviours.

Figure 5. Results obtained on a P3HT:PCBM thin film. (a) SSPG $\beta(L)$ curve obtained at 280 K, (b) Arrhenius plots of the dark and photo currents measured with two fluxes shown in the figure, (c) Arrhenius plots of the mobility lifetime products of the minority ($\mu \tau_{\text{min}}$) and majority carriers ($\mu \tau_{\text{maj}}$) for different fluxes, (d) MPC-DOS spectroscopy; the attempt-to-escape frequency was chosen equal to $10^8$ s$^{-1}$ to fix the energy scale and the measurement temperatures are displayed in the figure.

Figure 5d shows the MPC-DOS spectroscopy performed on this sample. Each set of symbols corresponds to a temperature at which the frequency of the modulation was varied and each point in a set corresponds to a frequency. The energy scale was fixed from equation (3) choosing an attempt-to-escape frequency of $\nu = 10^8$ s$^{-1}$. This value is rather low but it is an estimate for which the MPC spectra gather at low temperature to describe a band tail and they also gather at high temperature to describe a distribution of deep states. This DOS is in fair agreement with the one proposed by Street et al. [20, 21]. This low value of $\nu$ would increase if we took the variations of the ‘gap’ of the film into account as it was the case for some other materials [24]. However, we do not know if and how the ‘gap’ of BHJ films varies with temperature so we have assumed a constant value for it. Besides, even if we could apply some correction to the energy scaling, the $\nu$ value would remain rather small. It may explain the rather long time of stabilization of the photocurrent or the return to dark equilibrium condition that we have observed with this sample. Indeed, a low $\nu$ value implies a rather long traffic of
trapping and emission of carriers, especially emission, for the film to go from one state of equilibrium to the other, a property that was already observed for P3HT [25].

5. Conclusion
We have built a bench that allows the performing of several characterization experiments of thin photoconductive films dedicated to the solar industry. With this set up one can estimate the film transport parameters under steady or modulated illumination as well as with interferences shone onto it, all these experiments being performed with the sample in the same state (same temperature, same vacuum,..). The accuracy of these measurements was validated by experiments performed on a well known material, a-Si:H, and all the usual values of the transport parameters as well as the DOS distribution were found again. Then, we have investigated the transport properties of a blend of P3HT and PCBM. One of the advantages of this all-in-one system is that the film is never put back in the air between two subsequent experiments preventing it from any contamination. Though the transport in this organic material may be different of that in inorganic disordered semiconductors, recent publications suggest that the global picture is very similar in both films, and indeed, the results obtained on P3HT:PCBM are very close to those obtained on a-Si:H. It is clear that more investigations are still needed to fully understand all the processes implicit to the transport in organic thin film. Nevertheless, the present characterizations could be an asset in optimizing organic thin films transport properties before their incorporation in a solar device.

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