SIMULATION OF THE PRE- AND POST-TRANSIT TIME OF FLIGHT METHODS IN AMORPHOUS SILICON-LIKE, N⁺-I-P⁺ -CELLS
SIMULATION DES METHODES DE PRE- ET POST-TRANSIT DE LA TECHNIQUE TEMPS DE VOL POUR LES CELLULES N⁺-I-P⁺ EN MATIERAU DE TYPE a-Si:H.

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ABSTRACT
In this paper, we study, by numerical simulation, the Transient Photocurrent (TPC) resulting from the application of the 'Time Of Flight' (TOF) technique to a-Si:H n⁺-i-p⁺ cell by using a typical Density Of States (DOS) of amorphous silicon. The pre- and post-transit methods, currently used to probe the energy distribution of localised states, are then applied to reconstruct the proposed DOS from the simulated TPC. We demonstrate that the two methods of reconstruction are complementary and provide an efficient tool of determining the transit time.

RESUME
Dans cet article, nous étudions, par simulation numérique, le photocourant transitoire (PCT) résultant de l'application de la technique 'temps de vol' (TOF) à une cellule n⁺-i-p⁺ en a-Si:H en utilisant une densité des états (DOS) typique au silicium amorphe. Les deux méthodes de pré et post-transit, couramment utilisées pour déterminer la distribution énergétique des états localisés dans le gap, sont ensuite appliquées au PCT simulé pour reconstruire la DOS proposée. On démontre que les deux méthodes de reconstitution sont complémentaires et fournissent un moyen de détermination du temps de transit.

1. INTRODUCTION
The degradation of a-Si:H solar cells presents a serious problem concerning their use in technological and commercial domain. To obtain a quality of a-Si:H more and more stable, several methods were developed. The TOF technique is one of the most used experiments for the opto-electric characterisation of a-Si:H solar cells. This technique uses, as a parameter, the transit time (or the flight time), τT, required for the photo-generated charge to cross the sample after a rapid optical excitation of a reverse biased n-i-p diode [1, 2, 3]. In this paper, we present numerical simulation results of the TOF technique applied to the n⁺-i-p⁺ structure in the current mode. We examine the degree of reconstruction of the actual DOS proposed for the TPC simulation. We demonstrate that the pre- and post-transit methods, applied to the simulated TPC to reconstruct the DOS, are complementary and allow for the determination of the transit time τT.

2. TOF TECHNIQUE
Fig. 1. depicts the principle of the TOF method. The a-Si:H-like sample consists of a n⁺-i-p⁺ structure with electrodes on either side.

First, the voltage pulse and, with a certain delay ∆t, the short laser pulse of highly absorbed light are applied to the sample. Electron-hole pairs are then generated near the illuminated junction and separated by the applied electric field. This separation is such that the front electrode collects all charges of the same sign, while charges of the opposite sign cross the sample towards the other electrode. During the transient, the charge of the photogenerated carriers interacts with traps existing along the intrinsic region. Therefore, the measured TPC will give information on the localised states energy distribution of the material to be characterised.

3. PRE AND POST-TRANSIT METHODS
Several spectroscopic methods have been put forward for the interpretation of TPC measurements in amorphous
semiconductors. In this paper, we emphasise on the pre- and post-transit methods [4].

The pre-transit method is applied to the TPC in the pre-transit region and probes states having release times shorter than \( t_T \). This method is based on the multiple-trapping model developed by Tiedje and Rose [5], and Orenstein and Kastner [6]. It is assumed here that the density of states is distributed continuously and the carriers thermalise without loss by recombination or extraction after completion of transit. Thermalisation occurs such that, at a time \( t \) following the optical excitation, most of the carriers are concentrated in states close to a "thermalisation energy", \( E_{\text{th}} \). For the case where transport occurs by holes, \( E_{\text{th}} \) is given by

\[
E_{\text{th}} = E_v + kT \ln (\nu t)
\]

where \( \nu \) is the attempt-to-escape frequency for the localised states, \( T \) is the temperature and \( k \) is Boltzmann’s constant. This model allows the determination of the DOS, \( g(E_{\text{th}}) \), at energy \( E_{\text{th}} \) according to the following expression:

\[
g(E_{\text{th}}) = \frac{C}{I(t)I}
\]

where \( C \) is a constant.

The post-transit method, on the other hand is applied to the post-transit region of the TPC. In this case, the TPC is controlled by thermal emission of carriers that have been trapped in states having a release time longer than \( t_T \). The DOS, \( g(E_{\text{th}}) \), is then determined by the expression:

\[
g(E_{\text{th}}) = C' \cdot J(t)I
\]

4. **TPC SIMULATION**

Our sample consists of a 0.5 \( \mu m \) a-\( \text{Si:H} \) \( n^-\text{-}i\text{-}p^+ \) cell, where the front illuminated side is the \( n \) region which is positively polarised. It means that we study transport of holes. For computation of the TPC, we use Poisson’s equation (eq (4)), the continuity equations (eqs (5) and (6)) and the multi-trapping equations (eqs (7) and (8)).

\[
\frac{\partial p(x,t)}{\partial t} = - \frac{1}{q} \frac{\partial J_p}{\partial x} \sum_i T^p_i (x, E_i, t) - \sum_i T^p_i (x, E_i, t) + G(x, t)
\]

\[
\frac{\partial n(x,t)}{\partial t} = \frac{1}{q} \frac{\partial J_n}{\partial x} \sum_i T^C_i (x, E_i, t) - \sum_i T^C_i (x, E_i, t) + G(x, t)
\]

\[
\frac{\partial p_l (x, E_i, t)}{\partial t} = T^p_l (x, E_i, t) - T^C_l (x, E_i, t)
\]

\[
\frac{\partial n_t (x, E_i, t)}{\partial t} = T^C_l (x, E_i, t) - T^p_l (x, E_i, t)
\]

\[
\psi (x,t) = - \frac{q}{\varepsilon \varepsilon_0} \left[ p(x,t) - n(x,t) + \sum_i p_i (x, E_i, t) - \sum_i n_t (x, E_i, t) \right]
\]

where \( \psi (x,t) \) is the potential through the sample. \( p(x,t) \) and \( n(x,t) \) are the free holes and electrons concentrations. \( p_i (x, E_i, t) \) and \( n_t (x, E_i, t) \) are the hole and electron concentrations trapped by the \( i^{\text{th}} \) energy level \( E_i \) of the sub-divided gap.
Simulation of the pre- and post-transit time of flight methods in amorphous silicon-like n+--i--p+ -cells

\[ T^C_p(x,E_i,t), T^C_n(x,E_i,t) \] are, respectively, the net hole and electron trapping rates at the position \( x \), in the instant \( t \), at a level \( E_i \) of the conduction band tail.

\[ T^C_p(x,E_i,t) = C^C_p p(x,t) n_i(x,E_i,t) - e^C_p(E_i) \left[ N^C_p(E_i) - n_i(x,E_i,t) \right] \]

\[ T^C_n(x,E_i,t) = C^C_n n(x,t) n_i(x,E_i,t) - e^C_n(E_i) n_i(x,E_i,t) \]

Equation (12)

Equation (13)

\( C^C_p, C^C_n \) are capture coefficients for holes and electrons and \( e^C_p, e^C_n \) are emission probabilities for the conduction band tail states given by

\[ e^C_p(E_i) = C^C_p N_v \exp \left( \frac{E_v - E_i}{kT} \right) \]

\[ e^C_n(E_i) = C^C_n N_v \exp \left( \frac{E_i - E_c}{kT} \right) \]

Equation (14)

The total current density (\( J \)) is given by the sum of hole (\( J_p \)), electron (\( J_n \)) and displacement (\( J_d \)) currents.

\[ J(t) = \frac{1}{d} \int_0^d \left( J_p(x,t) + J_n(x,t) \right) dx + \varepsilon E_O \frac{d}{d} \int_0^d \frac{d}{d} \zeta(x,t) dx \]

Equation (15)

where

\[ J_p(x,t) = q \mu_p \left[ p(x,t) \zeta(x,t) \frac{d}{d} \right] \]

\[ J_n(x,t) = q \mu_n \left[ n(x,t) \zeta(x,t) \frac{d}{d} \right] \]

Equation (16)

Equation (17)

\( d \) is the sample thickness, \( \varepsilon E_O \) the permittivity and \( \zeta(x,t) \) the electric field distribution.

As initial conditions, we assume a homogeneous electric field distribution along the sample, the instantaneous generation of electron-hole pairs according to the exponential law given by the absorption coefficient \( \alpha \) and the thermal equilibrium for the initial occupation of the band tails. Boundary conditions are given by \( \psi(0,t) = U_O + U_i \) and \( \psi(d,t) = 0 \), where zero and \( d \) are the positions of the front and rear electrodes respectively, \( U_O \) is the applied voltage and \( U_i \) is the built-in voltage.

The voltage across the sample is assumed to be constant at all times and

\[ \int_0^d \zeta(x,t) dx = U_O + U_i \]

so the transient current density \( J(t) \) can be calculated simply from the hole and electron current.

Equilibrium is assumed for the region adjacent to the metal end-contacts, so that the relation \( n_p = n_i^2 \) is verified at these points (\( n_i \) is the intrinsic concentration).

The proposed DOS (for the valence band tail) used in this simulation is shown in Fig.2.

\[ \begin{align*}
E & \quad \text{DOS (cm}^3\text{eV}^{-1}) \\
0.0 & 10^{12} \\
0.2 & 10^{14} \\
0.4 & 10^{16} \\
0.6 & 10^{18} \\
0.8 & 10^{20} \\
1.0 & 10^{22}
\end{align*} \]

Equation (18)

The system of equations describing charge transport has been solved using finite difference method. To simplify, we have considered only the one-dimensional case in which, the different variables are function of the spatial co-ordinate \( x \) and of the time \( t \) [7, 8].
5. SIMULATION RESULTS

Fig.3 shows the simulated hole TPC under 2V reserve bias, with $T=300\,^\circ\text{K}$ and $T_r=520\,^\circ\text{K}$. The photogenerated charge $Q_0$ is $6.3 \times 10^{-7} \, \text{Ccm}^{-2}$ with $\alpha=6 \times 10^5 \, \text{cm}^{-1}$.

The curve shows a dispersive transport of holes through the intrinsic region. At very short times, lower than about $10^{-11} \, \text{sec}$, the TPC is dominated by initial trapping of free carriers in the tails states, followed by the pre-transit thermalisation. After, the TPC decays according to the 'post-transit' regime defined above. The intersection point $t_T$, separating the two regimes represents the transit time, we have $t_T \approx 10^{-7} \, \text{sec}$.

According to this curve, we can notice that the reconstruction gives a result that agrees reasonably well with the proposed DOS over a wide energy range. Besides, the two methods are complementary and the transit time $t_T$ can be calculated from the energy level $E_T$ using the thermalisation relation $E_T = E_V + kT \ln(v_t)$, $E_T$, being the level above (below) which the DOS calculated by the pre- (post-) transit method begins to diverge.

The calculated $t_T$ value is shown in Table 1 together with the $t_T$ value deduced from the TPC.

<table>
<thead>
<tr>
<th>DOS (eV)</th>
<th>TPC $t_T$ (sec)</th>
<th>$t_T$ (sec)</th>
</tr>
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<tbody>
<tr>
<td>0.3</td>
<td>$1.084 \times 10^{-7}$</td>
<td>$10^{-7}$</td>
</tr>
</tbody>
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the value of $t_T$ calculated from $E_T$ is close to that determined from the TPC within a precision of about 8.12%.

CONCLUSION

In this work, we have simulated transient photoresponse of a n+-i-p+ structure obtained by the TOF technique. We have demonstrated that the transit time can be determined from the DOS obtained by application of both the pre- and post-transit TOF methods.

REFERENCES