

# Correlation between transport properties of a-Si:H layers and cell performances incorporating these layers

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## Abstract

Using the new 'quality parameter',  $\mu^0\tau^0$ , the authors were able to show, for the first time, a clear correlation between transport properties of a series of a-Si:H films (grown at various deposition temperatures) and the efficiency of p-i-n cells incorporating the same material as i-layer. In this paper, additional experimental data are presented sustaining, on one hand, the validity of the proposed 'quality parameter',  $\mu^0\tau^0$ , and on the other hand, the existence of a correlation between cell performances and transport properties. Furthermore, limitations of this correlation, due to technological problems (e.g., chemical contamination by Na, O, ...) involved in the practical fabrication of a-Si:H solar cells are also illustrated and discussed.

## 1. Introduction

The absence of correlation between transport properties in a-Si:H films and the performance of a-Si:H solar cells performance has so far been frustrating [1,2]. Practically, all past attempts at demonstrating such a correlation have either failed or have been inconclusive. Thus, the improvement of solar cells has too often been completely disconnected from actual material research, this being mainly due to the absence of a reliable monitor for material quality.

The transport properties of the material are usually given in terms of mobility lifetime products,  $\mu\tau$ , for both minority and majority carriers; these products may be deduced from steady-state photoconductivity measurements (SSPC) and from the steady-state

photocurrent grating (SSPG) technique, respectively. However,  $\mu\tau$  values (namely band mobility  $\times$  recombination time products,  $\mu^0\tau^R$ ) experimentally derived, in this manner, are strongly dependent on the occupation of the dangling bonds. Thus, these  $\mu\tau$  values cannot be regarded as quality parameters, since the occupation functions of the dangling bonds in individual layers are very different from their distributions throughout the i-layer of solar cells.

Recently, our group has proposed to use as a quality indicator for a-Si:H layers the product band mobility  $\times$  capture time,  $\mu^0\tau^0$  [3]. Based on a simple model of recombination via dangling bond states,  $\mu^0\tau^0$  can be easily deduced from either photoconductivity or SSPG data, depending on the position of the Fermi level in the film [4]. One should note, that this new parameter,  $\mu^0\tau^0$ , takes into account both the disorder (which governs the mobility) as well as the defect density (via the capture time,  $\tau^R$ ).

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## 2. Definition and evaluation of $\mu^0\tau^0$ products

Transport properties in a-Si:H can be described in terms of band mobility  $\times$  free carrier recombination time,  $\mu^0\tau^R$ , and generally deduced from SSPC or SSPG. Photoconductivity deduced from SSPC is defined as

$$\sigma_{ph} = e(\mu_n^0 n_f + \mu_p^0 p_f) = eG(\mu_n^0 \tau_n^R + \mu_p^0 \tau_p^R), \quad (1)$$

where  $e$  is the elementary charge,  $G$  is the generation rate,  $n_f$ ,  $p_f$  are the free electron and free hole density and  $\mu_n^0$ ,  $\mu_p^0$  are their respective mobilities;  $\tau_n^R$  and  $\tau_p^R$  are the recombination times of the carriers. Ambipolar diffusion length measured by SSPG can be written as

$$L_{amb}^2 = \frac{kT}{e} \frac{\mu_n^0 \tau_n^R \mu_p^0 \tau_p^R}{\mu_n^0 \tau_n^R + \mu_p^0 \tau_p^R} C, \quad (2)$$

where  $kT$  is the thermal energy and  $C$  is a constant between 1 and 2 [3]. The position of the Fermi level  $E_F$  in the material can be expressed by the parameter  $b = \mu_n^0 n_f / \mu_p^0 p_f = \mu_n^0 \tau_n^R / \mu_p^0 \tau_p^R$  [5], which can be experimentally evaluated from the following expression (resulting from Eqs. (1) and (2)):

$$\frac{b}{(b+1)^2} = \frac{L_{amb}^2 e^2 G}{kT \sigma_{ph} C}, \quad (3)$$

In the framework of a simple recombination model through dangling bond states [6], and under sufficiently high illumination conditions (which correspond to the usual conditions for SSPC and SSPG), the recombination times  $\tau_n^R$  and  $\tau_p^R$  can be written as

$$\begin{aligned} \tau_n^R &= \frac{1}{v_{th} N_{db} (\sigma_n^0 f^0 + \sigma_n^+ f^+)}, \\ \tau_p^R &= \frac{1}{v_{th} N_{db} (\sigma_p^0 f^0 + \sigma_p^- f^-)}, \end{aligned} \quad (4)$$

where  $v_{th}$  is the thermal velocity,  $N_{db}$  is the dangling bond density and  $f^0$ ,  $f^+$ ,  $f^-$  are the dangling bond occupation functions in steady-state equilibrium (under illumination).

Using the Eq. (4), we can now define transport

parameters  $\mu^0\tau^0$  which are 'true' material parameters and do not depend on the dangling bond charge:

$$\begin{aligned} \mu_n^0 \tau_n^0 &= \mu_n^0 \frac{1}{v_{th} N_{db} \sigma_n^0}, \\ \mu_p^0 \tau_p^0 &= \mu_p^0 \frac{1}{v_{th} N_{db} \sigma_p^0}. \end{aligned} \quad (5)$$

A simplification can be introduced at this point, by assuming that  $\mu_n^0 \tau_n^0 = \mu_p^0 \tau_p^0 = \mu^0 \tau^0$ . This statement is sustained by previous time of flight (TOF) results obtained by our group [4,7].

Using the analytical forms for these occupation functions given in Refs. [6,8], expressed in terms of the free electron and free hole densities and their capture times on the specific dangling bond states, one can show [4,9] that

$$\begin{aligned} \mu^0 \tau^0 &= \frac{\sigma_{ph}}{eG} \frac{1}{z} \quad \text{with} \\ z &= \left( \frac{\sigma_n^0}{\sigma_n^+} \frac{1}{b} + 1 + \frac{\sigma_p^0}{\sigma_p^-} b \right). \end{aligned} \quad (6)$$

Expression (6) offers a very convenient way to evaluate  $\mu^0\tau^0$  in all types of a-Si:H.  $L_{amb}$  does not appear explicitly in this relation, but intervenes in the evaluation of the correction factor  $z$  (through the parameter  $b$ , see Eq. (3)).

For *truly intrinsic* (compensated or 'midgap') material, where the Fermi level is near midgap,  $b \approx 1$  and  $z \approx 1$ . In this case,  $\sigma_{ph}$  is the proper parameter to describe material quality. For *n-type* material (or even for undoped slightly n-type films, as soon as  $b > \sigma_p^- / \sigma_p^0$ ) or for *p-type* material (as soon as  $b < \sigma_n^0 / \sigma_n^+$ ), the material quality parameter  $\mu^0\tau^0$  is given by  $L_{amb}$  and

$$\mu^0 \tau^0 \approx L_{amb}^2 \frac{1}{C} \frac{e}{kT} \frac{\sigma^\pm}{\sigma^0}. \quad (7)$$

Note, that the above procedure for the determination of the quality related parameter  $\mu^0\tau^0$ , call for a precise knowledge of the capture cross-section ratios  $\sigma_n^+ / \sigma_n^0$  and  $\sigma_p^- / \sigma_p^0$ . Unfortunately, values of these ratios found in the literature are controversial. However, recent studies based on the dependence of  $\mu^0\tau^0$  as a function of doping [9], as well as degradation studies [10], suggest a value of  $\sigma^\pm / \sigma^0 = 50$ , which

is consistent with the value obtained from previous TOF studies [7].

### 3. Experimental

Two series of samples, consisting of layers and p-i-n cells incorporating the same material as an i-layer, were deposited by the VHF glow discharge deposition technique (at  $f = 70$  MHz) [11]. Deposition temperature was varied between 120°C and 320°C and the thicknesses of the films varied between 2.2  $\mu\text{m}$  and 5  $\mu\text{m}$ . Standard p-i-n solar cells were deposited on Asahi type U TCO-coated glass with an intrinsic layer thickness of 0.6  $\mu\text{m}$ . Cell efficiencies were determined under standard AM1.5 illumination, using a two-source solar simulator (Wacom WXS.140S-10). Steady-state experiments were performed on a-Si:H layers deposited on glass substrates (Corning 7059) with two coplanar Al contacts evaporated on top of the layer with a 0.5 mm gap; a Kr laser ( $\lambda = 647$  nm) was used for sample illumination. All samples were annealed at 180°C for 2 h prior to their characterisation (in the annealed state). Solar cells were degraded during 3 weeks by a white light illumination at 100 mW/cm<sup>2</sup> (array of Philips PL-L24W/95/4P lamps) at 47°C, whereas films were light-soaked during 4 weeks by a 6 sun high pressure sodium lamp (spectral maximum at 600 nm).

### 4. Results

Undoped a-Si:H layers exhibit usually a slightly n-type character in the annealed state. This behaviour may be traced back to the effect of unintentional doping by impurities (mainly oxygen); Fig. 1 illustrates the slightly extrinsic character of layers in the annealed state. The limit between 'truly intrinsic' and 'slightly extrinsic' character is given by the ratio of capture cross-sections  $\sigma^\pm/\sigma^0$ , assumed here to be 50. We observed a slight shift towards a more extrinsic character (or n-type) as the deposition temperature is raised from 120°C. This could be attributed to increased incorporation of impurities at higher temperatures. One also observes that, after degradation, the layers become 'truly intrinsic'.

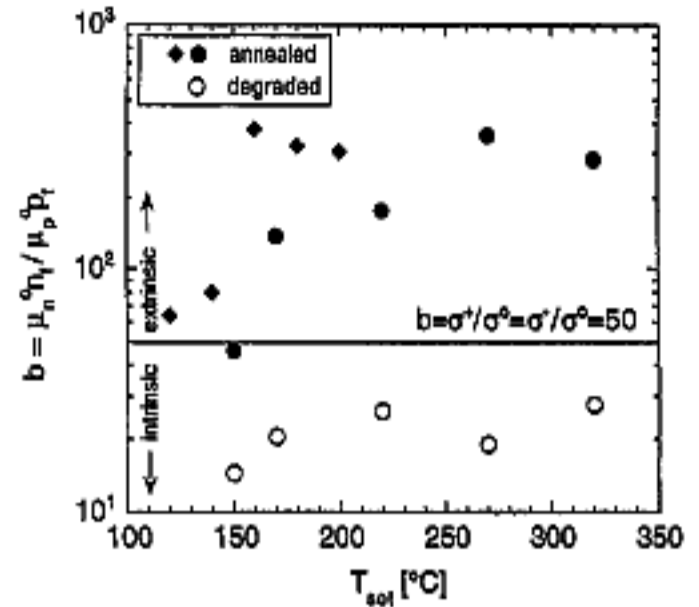


Fig. 1. Variation in the value of the parameter  $b$  (see Eq. (5)) as a function of the deposition temperature,  $T_{\text{set}}$ , in the annealed and degraded state, for two temperature-series of undoped layers (circles: first series, squares: second series).

Fig. 2 shows the quality related  $\mu^0 \tau^0$  products for individual layers and the efficiencies of corresponding solar cells; a satisfactory correlation for deposition temperatures,  $T_{\text{set}}$ , up to 220°C, in the annealed state. Both  $\mu^0 \tau^0$  and efficiency increase with the increase of  $T_{\text{set}}$ . For higher deposition temperatures, the efficiency starts to decrease whereas  $\mu^0 \tau^0$  remains almost constant. For the degraded

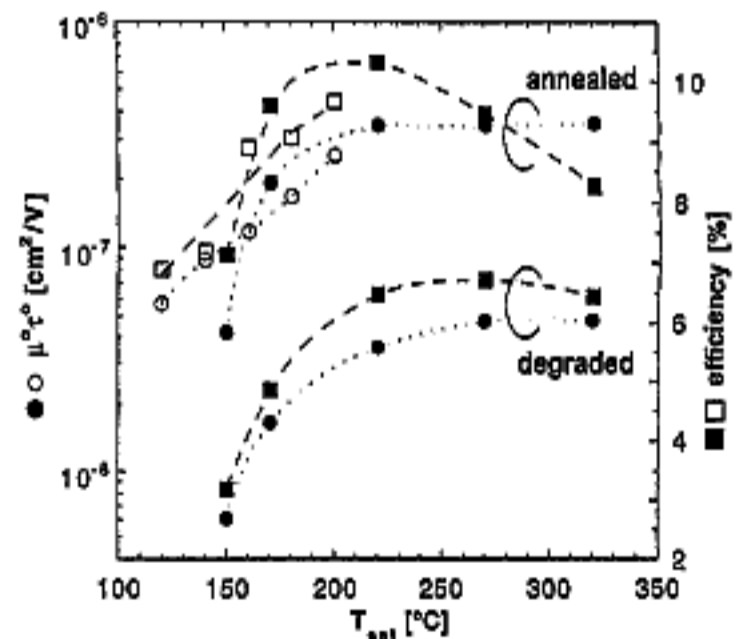


Fig. 2.  $\mu^0 \tau^0$  products evaluated on two series of  $\sim 2.5$   $\mu\text{m}$  thick, undoped films and corresponding efficiencies of solar cells incorporating the 'same' films as an i-layer, in the annealed state and in the degraded state (solid marks: first series, open marks: second series).

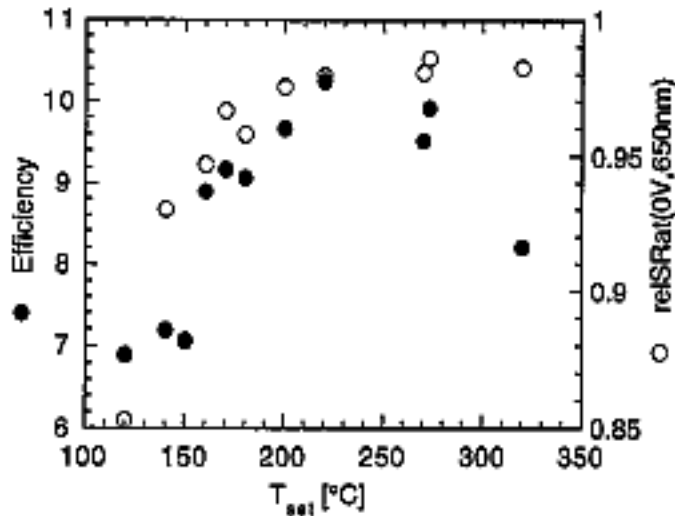


Fig. 3. Efficiency and corresponding normalised spectral response at 0 V and 650 nm for the two series of solar cells in the annealed state.

state, the correlation between  $\mu^0\tau^0$  and the efficiency is good at all deposition temperatures.

## 5. Discussion

In order to predict, from the i-layer quality (using the  $\mu^0\tau^0$  value), the cell performance, it is obvious that the latter should be controlled by the bulk properties of the i-layer. The decrease in the efficiencies of the (annealed) cells deposited at temperatures above 220°C are probably due to a deterioration of interface properties or to interdiffusion of impurities (from the substrate, the TCO or the p-doped layer) into the interface region of the i-layer. This affirmation is confirmed by a measurement of the (relative or normalised) spectral response of the solar cells at 0 V bias voltage and 650 nm as a function of  $T_{set}$ . At this wavelength, generation occurs throughout the entire i-layer thickness. Thus, the collection reflects the bulk properties of the i-layer and should be quite insensitive to the interface regions. Fig. 3 shows, indeed, that the normalised spectral response for annealed cells deposited at temperatures over 220°C exhibit no decrease despite the drop in efficiency.

## 6. Conclusion

By taking into account both the mobility and the defect density, the proposed quality, parameter  $\mu^0\tau^0$ , which is independent of the Fermi level position, should avoid most of the problems encountered in the correlation between i-layer properties and solar cell performance. In the context of layer characterisa-

tion, quality is monitored either by  $\sigma_{ph}$  (for truly intrinsic layers) or  $L_{amb}$  (for slightly extrinsic films); the intrinsic or extrinsic character is given by the magnitude of the parameter  $b$  (a parameter derived from SSPC and SSPG); it would change with the deposition condition of the films (temperature, impurity content, ...), as well as the degradation state. Therefore, SSPC or SSPG alone cannot be used as a reliable tool for all films.

We have shown that this quality-related  $\mu^0\tau^0$  is a valuable tool to predict the potential of a given material for its application as an active i-layer in the solar cell. In general,  $\mu^0\tau^0$  correlates well with the measured cell performance. Nevertheless, actual cell performance will not only depend on the bulk properties of the i-layer, but also on the doped layers and interfaces.

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