Determination of Internal Electrical Field Profile in a-Si:H Solar Cells

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ABSTRACT: Basic methods for the determination of internal electrical field in a-Si:H solar cells, derived from the standard Time of Flight (TOF) technique, are presented. One of these methods, based on charge collection, is very attractive; is is particularly simple, does not need high time resolution and is insensitive to the transport dispersion. It allows characterisation of the internal electrical over the whole thickness of the i-layer when bifacial p-i-n a-Si:H solar cells are used. Use and limits of this specific method are presented and discussed. Furthermore, some examples of field engineering in p-i-n are shown.

1. INTRODUCTION

The improvement of the stabilised efficiency of a-Si:H solar cells is of paramount importance for the future of this technology. The basic approach for solving this problem has been to search for more stable materials. More recently, several studies have focused on alternative ways to improve the efficiency of a degraded cell by changing the cell **design**. In a degraded cell, poor collection is due to the combination of two effects: a deformation (and lowering) of the internal field and an increase in defect density. If one can keep the internal field high, collection can be significantly improved. The strategy here is to enhance the field in those specific, critical regions of the degraded cell by "defect engineering", "band gap engineering" or "micro-doping" [1-4]. The practical success of these methods depends on the availability of a tool for the **experimental determination of the internal electrical field profile**.

Depth characterisation of solar cells is usually performed using the spectral response measurement. This technique is used to identify low collection regions inside the intrinsic layer. However, this method does not permit one to separate between the effects of a low internal field and that of high defect densities. A direct measurement of the internal electrical field profile is therefore necessary.

Two basic methods, both derived from the standard Time of Flight (TOF) technique, have been proposed for this purpose. The first one introduced by Street [5], more recently applied by Könenkamp et al. [6], relies on the current transient of a drifting sheet of charge. Its major drawback is its poor spatial resolution (at least with standard TOF equipment) and its inadequacy in the case of non-dispersive transport. The second method, proposed by Vanderhaghen et al [7], is based on charge collection. Both methods involve the generation of electron-hole pairs at the surface and the subsequent drift of one type of carriers through the device.

Contrary to Street's method, the Vanderhaghen's method allows one to probe the field on both sides of a p-i-n cells, if semitransparent contacts are provided on both sides. Thus, this method has been successfully applied to measure internal field profiles in thin (bifacial) solar cells by measuring electron and hole collection [4,8]. However, as the interpretation of the results are not straightforward, a detailed discussion and analysis of what the method can achieve and what are its limitations is needed and will be given hereunder.

2. METHODS

2.1 Street's method

Provided the drift mobility can be considered to be constant as a function of position and also as a function of electric field, and if the collection efficiency is unity, then the photocurrent induced by the drifting sheet of carriers can be easily related to the field profile F(x). The field strength at time t can be expressed by the transient current i(t) due to the drifting carrier sheet:

$$F(t) = i(t)\frac{L}{Q\mu}$$

where L is the sample (or i-layer) thickness, Q the charge of the drifting carrier sheet and μ the drift mobility. The position of the sheet at time t x(t) is given by

$$x(t) = \mu \int_0^t F(t')dt'$$

The charge Q is determined from the total collected charge under sufficiently high reverse bias (100 % collection efficiency). The drift mobility μ may be deduced from the transit time under the same total collection condition.

The principal drawbacks of this method arise from the constant drift mobility condition and the need of a well-defined sheet of drifting carriers. Thus, carrier transport has to be non-dispersive and one is forced to do the experiment under sufficiently high reverse bias, especially for degraded solar cells. Furthermore, a fast transient recorder as well as short laser pulses are needed to achieve a useful spatial resolution for this technique (the spatial resolution is directly related to the time resolution). To get a spatial resolution Δx=10 nm (1/30 of the i-layer thickness of a standard solar cell) near the p/i interface, where fields F higher than 10^4 Vcm^{-1} are present, one needs a rise time t_R of the transient recorder (and a laser pulse length) smaller than 100 ps ($\Delta x = t_R \mu F$)

Practically, the electrical field F(x) can only be probed in the first half of the (p-side) i-layer. Determination of F(x) near the n/i interface can only be achieved by photogenerating carriers through the back contact (n-layer) and by measuring the current due to the drifting holes. However, due to the dispersive nature of hole transport at room temperature, this procedure can only be applied at higher temperatures where hole transport becomes non-dispersive.

Note that the experiment has generally to be performed in the charge collection mode to avoid RC distortion of the signal due to the large capacitance of thin p-i-n cells.

2.2 Vanderhaghen's method

This method is based on charge collection. An external electric field (pulsed, as in the standard TOF system, to insure an homogeneous application of this external field) is superimposed on the internal field. The aim is to create a zero field location at position x_o in the i-layer (cf. Fig. 1), where the internal field $F(x_o)$ is cancelled by the externally applied field F_{ext}. By changing this external (forward) polarisation, one can change the position x_o and, thus, probe the field profile. By measuring the charge collection Q and knowing the total photogenerated charge (which can be deduced from the collection under high reverse polarisation) on can easily determine the position x_o where internal and external field are opposite:

$$Q = Q_o \frac{x_o}{L}$$

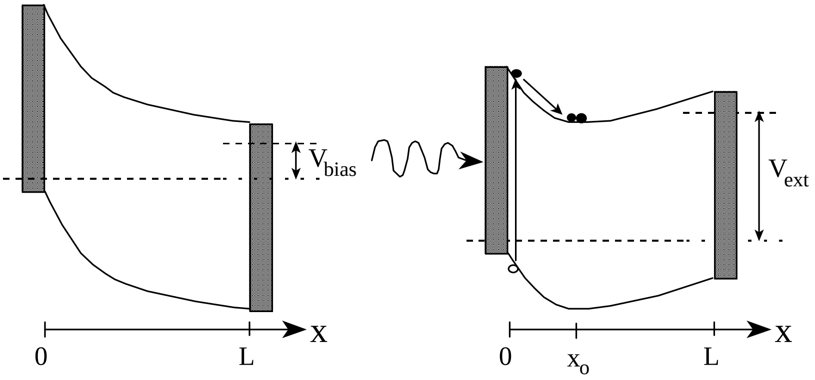


Figure 1: Cell under bias voltage V_{bias} before probing of the internal field (left) and during measurement (right). Zero field location is created at position x_o where the photogenerated carriers, which have drifted from the front contact, accumulate.

As we can see in Fig. 2, this method is "just" a reinterpretation of the charge collection curve, in term of internal field distribution. Note that measurements of the p-i-n cell under a given bias polarisation are also possible as shown by Longeaud et al. [9].

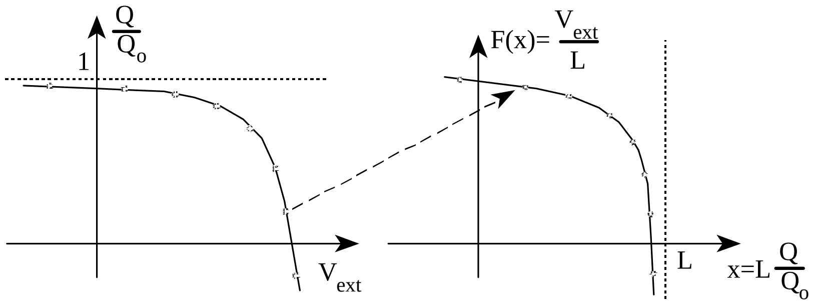


Figure 2: Correspondence between normalised charge collection (left) and field profile within the solar cell i-layer.

This method has several advantages over Street's one. It is insensitive to the transport regime (dispersive or non-dispersive), so it can be applied without any restriction to the n-side of the p-i-n cell by measuring holes. Because only the total collected charge is needed, speed requirement for the equipment (laser and transient recorder) is not an issue; RC distortion of i(t) has no consequence, and determination of the drift mobility is not necessary. Spatial resolution of Vanderhaghen's method is no more related with the speed of the recorder, but with a precise determination of the charge collection and also with the absorption length of the light used for the generation. Even for very strongly absorbed light, the given generation profile tends to systematically underestimates the field values near the p/i or n/i interfaces, especially when high field gradients are present.

Despite the simplicity of the Vanderhaghen's method, its applications and interpretation are not obvious and need some precautions. During the measurement, total collection (100% collection efficiency) does not occur (a limited collection is, in fact, the aim of the technique); this implies that one must be sure, to ensure the accuracy of the determined field profile, that collection was limited by a zero field location in the i-layer and not by the drift length of the carriers. This condition can unfortunately not be easily checked. Therefore, the internal field gradient tends to be overestimated (x_o is underestimated). This latter effect, together with the underestimation of the field near the p/i or n/i interface, lead, as a consequence, to the built in voltage being underestimated, especially on degraded p-i-n cell or diodes with a strong field gradient near the interfaces (p/i or n/i). Another limitation is related to the shape of the internal field that the method is able to probe successfully. Since one has to create a zero field location (a potential well) inside the i-layer, this determination of the internal field profile F(x) is limited to regions where

$$\frac{d^2F}{dx^2} > 0$$

when electrons are drifting or

$$\frac{d^2F}{dx^2} < 0$$

when the current is due to drifting holes. Some examples of p-i-n cell and the expected field profiles that should be obtained from the measurement (from both sides) are given schematically in Fig. 3. Field profile of case a) can be determined correctly, whereas, in case b), a "feature" of the profile will not be recognised. Example c) shows a case where the method is completely unsuitable.

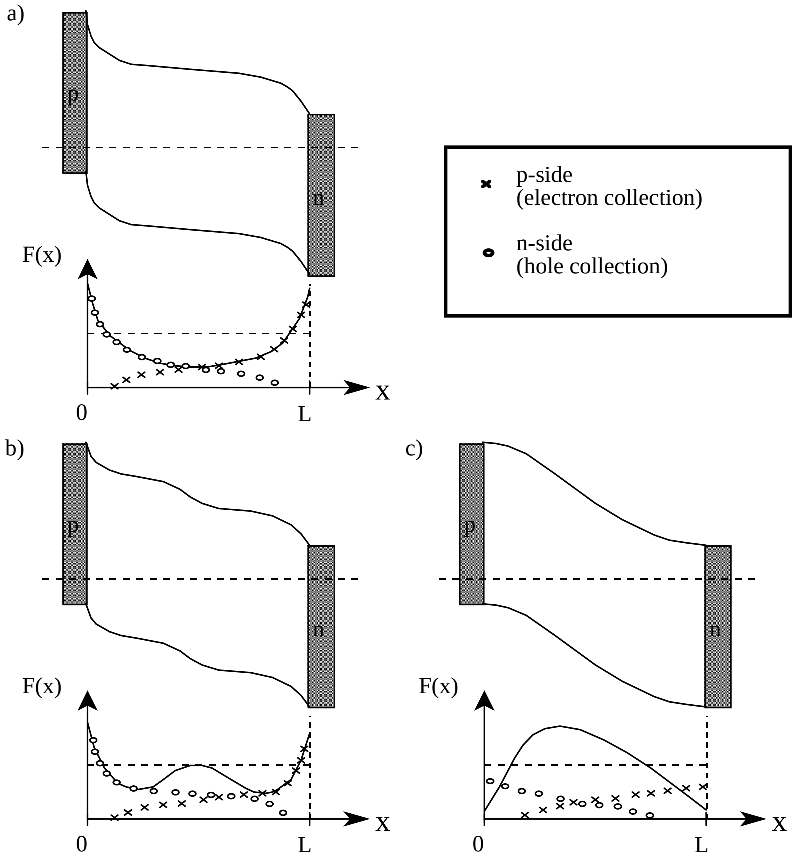


Figure 3: Three schematic examples of p-i-n cell with different band diagrams and their corresponding internal field profile (solid line). For each case the internal field profile which is expected from charge collection (for electrons and holes), using Vanderhaghen's method, is also plotted. Case a) represents a standard p-i-n cell, whereas cases b) and c) illustrate the limit of the measurement technique.

As discussed by Longeaud et al. [9], several effects may affect the accuracy of the measurement: reliability of the measurement of Q and Q_0, interface effects, deep trapping, etc. To avoid some of these potential problems they proposed (in [9]) an improvement of the Vanderhaghen's method, which is closely related to the delayed field TOF technique. However with the modification proposed, the simplicity of the original method is lost as well as the requirement of a basic TOF equipment. As we will see from the following examples, a rather good analysis of the field profile is already possible with Vanderhaghen's basuc method.

3. EXPERIMENTAL

P-i-n diodes investigated here were deposited with the VHF-GD technique (at 70 MHz) described elsewhere [10]. The following structure was deposited on a textured TCO coated glass at 220 •C: 120 Å p^+a-Si:C:H / a-Si:H / 300 Å n^+µc-Si:H. A 1200 Å thick layer of ITO was used to provide a transparent back contact. For the "microdoping" studies, a part of the i-layer was intentionally doped (at ppm level) with boron or phosphine. Note that doping concentration refers to the gas phase concentrations (vppm) of phosphine or diborane in pure silane.

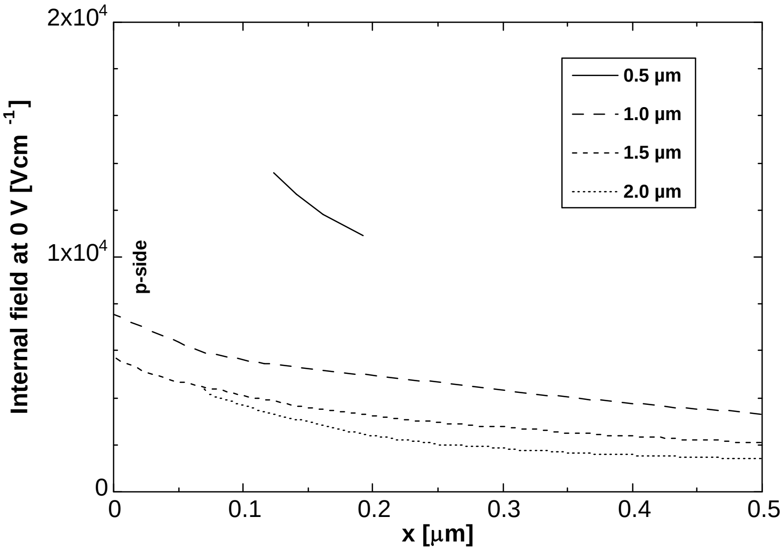
The determination of electrical field profiles was performed with a standard TOF set-up consisting of: a nitrogen pumped dye laser with a 3 ns pulse width (Laser Science), a Stanford Research DG535 pulse generator and a Tektronix 2440 oscilloscope with a 350 MHz bandwidth. Wavelengths between 420 and 470 nm for the laser pulse were used for the generation of electron hole pairs. Collected charges were obtained by integration of the current (TOF experiment performed in current mode) over a 1-100 µs time window.

Electrical field measurements were performed (if not otherwise stated) in the dark and at 0 V bias voltage.

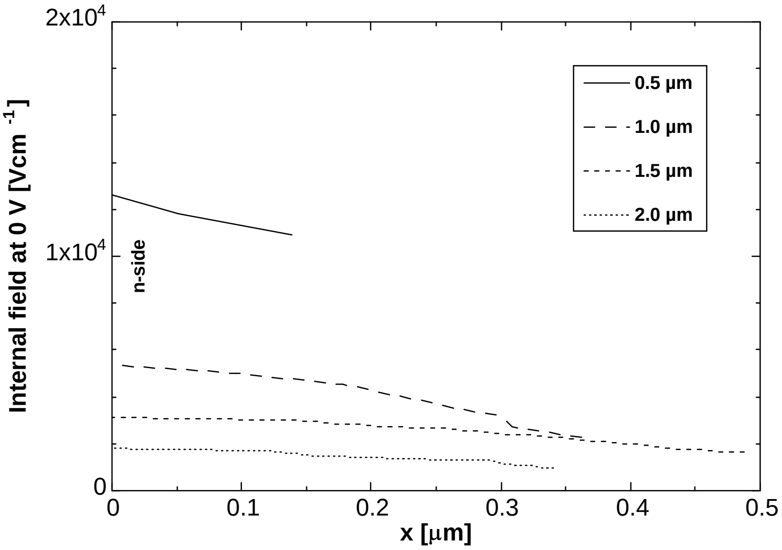
4. RESULTS AND DISCUSSIONS

As a first illustration of the method, the electrical field profile was determined on a series of annealed p-i-n cells with different i-layer thicknesses (0.5, 1, 1.5 and 2 µm). Electrical field profiles are given in Fig. 4a for the p-side (given by electron collection) and in Fig. 4b for the n-side (given by hole collection). One can see that the field strength scales reasonably well with the diode thickness. For the 1 µm and 1.5 µm thick diodes, the internal field is also rather constant throughout the i-layer. For the n-side, hole collection length did not exceed much 0.3 µm without applying a reverse external field. Therefore, field values for distances further than 0.2 µm from the n/i interface seem to be unreliable.

a)



b)



Figures 4: Internal field profile: (a) from the p/i-interface, (b) from the n/i-interface, for 4 annealed p-i-n cells with thicknesses ranging from 0.5 to 2 µm (at 0 V external bias) .

Field profiles of degraded cells were also investigated. Fig. 5 presents the field profile of a 0.5 µm thick p-i-n cell in the annealed state and in the light-soaked state (160 h at one sun, white light). As we expect, the field in the central part of the layer decreases with light soaking. We can observe also that a weak red bias light tends to restore (as is well known from spectral response measurements) to some extent the (undegraded) internal field profile. In this example, we can observe one of the limitations of the measurement, namely its disqualification for measuring accurate field values near the p/i-interface, and near the n/i-interface, when strong field gradients are present. Therefore, the built-in field is usually not measured correctly in these degraded cells.

As we can see in Fig. 5, measurement of field profile on illuminated diodes (with a bias light) is possible. However, a very restrictive limit has to be fulfilled for the light intensity of the bias light. TOF charge collection tolerates bias light only if carrier collection is achieved within the dielectric relaxation time. As the latter is inversely proportional to the conductivity of the sample, this strongly limits the possible intensity of the bias light. Measuring field profiles of solar cells under operating conditions is therefore (unfortunately) not possible with this method. However, the method remains a useful tool for studying field redistribution in the i-layer due to uniformly or strongly absorbed (weak) light.

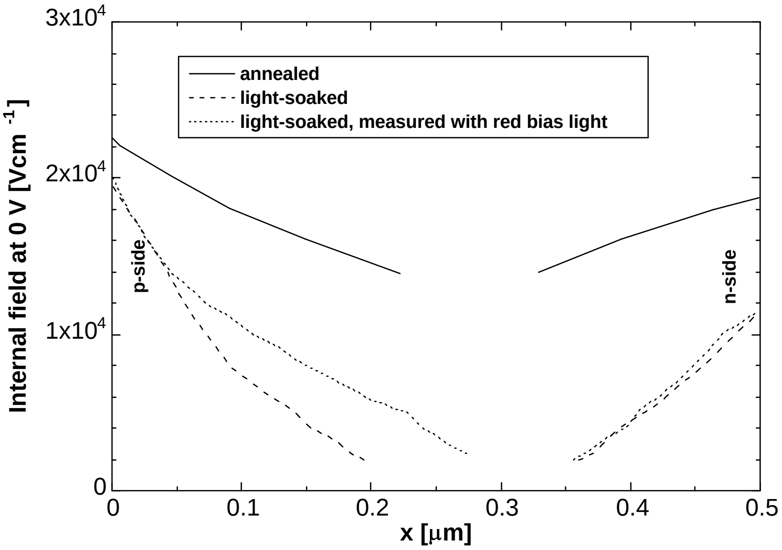


Figure 5: Internal field profile in a 0.5 μm thick p-i-n cell in the annealed and light-soaked state (at 0 V external bias); effect of a weak red bias light on the internal field profile in the light-soaked state.

By slightly doping a selected region of the i-layer of an a-Si:H solar, the field distribution may be significantly modified. Following measurements have been performed on several bifacial cells (0.5 μm thick), where a third of the i-layer (either the top, the middle or the bottom third) has been boron- or phosphine-doped (doping concentration: 2 vppm B_2H_6 or 1 vppm PH_3).

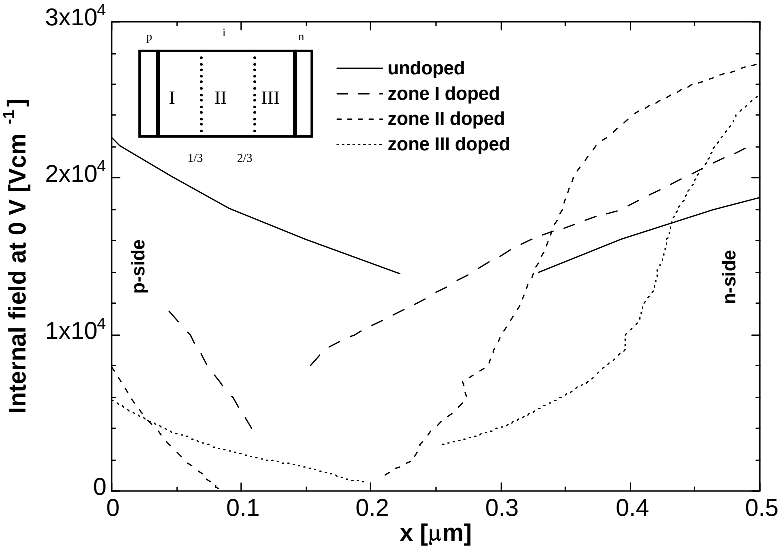


Figure 6: Internal field profiles in four 0.5 μm thick p-i-n cells, with specific parts of the i-layer slightly doped with boron.

Figure 6 shows the internal electrical field in p-i-n cells, where parts of the i-layer were boron-doped. The high internal field regions of the cells are found, as we expect, between the n-layer of the cell and the slightly boron-doped region of the i-layer. By concentrating the field in one part the i-layer, one observe consequently the reduction of the field strength in the remaining part of the cell. As already observed (cf. Fig 5), the values of the field near the interface (when strong field gradient are present) are not correctly reproduced (n-side of the field for the cell with doped zone III).

A similar example is given for phosphine-doped i-layers in Fig. 7.

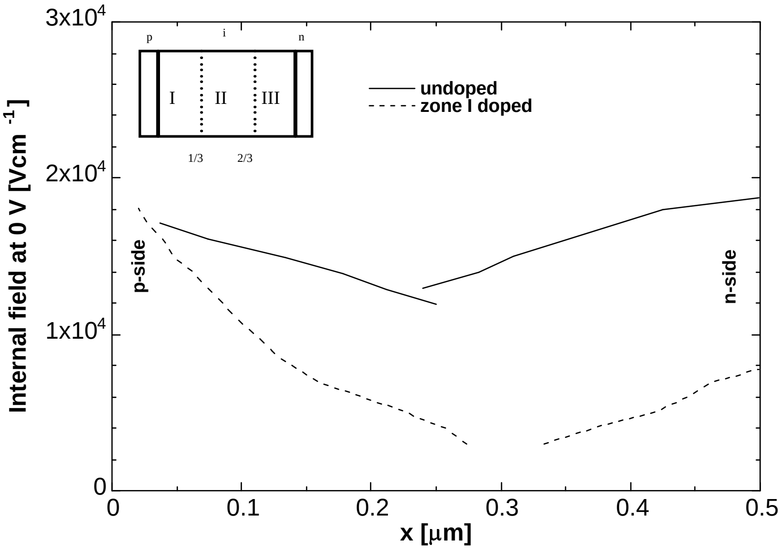


Figure 7: Internal field profiles in two 0.5 µm thick p-i-n cells, with specific parts of the i-layer slightly doped with phosphine.

4. CONCLUSIONS

"Defect engineering", "band gap engineering" or "micro-doping" have been recently successfully applied in p-i-n cells to improve the stabilised efficiency. However, this approach can only be followed up efficiently if one has a tool for the characterisation of the collection in the i-layer. Spectral response or DICE measurements [4] provide general information on collection lengths, but one yet needs to separate the effect of the mobility-lifetime product of the carriers and of the field.

With the help of several examples we have shown that the method proposed by Vanderhagen et al. is in this context a powerful tool for internal electric field profile measurements. It is simple, can be used on a standard TOF set-up and allows one to characterise almost the entire i-layer of (bifacial) p-i-n cell.

Further refinements of the technique proposed by Longeaud et al. [9] are not expected to improve much the accuracy of the field profiles. They certainly lack the simplicity of Vanderhagen's method and cannot be performed on a standard TOF set-up. Therefore, we believe that they are not suitable as a support for "defect/bandgap engineering" or "micro-doping" in p-i-n a-Si:H solar cells.

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