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A 3-phase model for VIS/NIR μC-Si:H p–i–n detectors

M. Vieira [a,*], A. Fantoni [a,b], M. Fernandes [a], A. Maçarico [a], R. Schwarz [a,c]

[a] *Electronics and Communications Department, ISEL, R. Conselheiro Emídio Navarro, P 1949-014 Lisbon Portugal*
[b] *FCT–UNL, Quinta da Torre, 2825 Monte da Caparica, Portugal*
[c] *Department of Physics, IST, Av. Rovisco Pais, 1 P-1096, Lisbon, Portugal*

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Abstract

The spectral response and the photocurrent delivered by entirely microcrystalline p–i–n-Si:H detectors are analysed under different applied bias and light illumination conditions. The spectral response and the internal collection depend not only on the energy range but also on the illumination side. Under ⟨p⟩- and ⟨n⟩-side irradiation, the internal collection characteristics have an atypical shape. It is high for applied bias and lower than the open circuit voltage, shows a steep decrease near the open circuit voltage (higher under ⟨n⟩-side illumination) and levels off for higher voltages. Additionally, the numerical modeling of the VIS/NIR detector, based on the band discontinuities near the grain boundaries and interfaces, complements the study and gives insight into the internal physical process.

Keywords: Photodetector; μc-p–i–n Devices; Photocurrent; Spectral response; Collection efficiency; Simulation

1. Introduction

The study of microcrystalline hydrogenated silicon μc Si:H based devices is still at an early stage [1,2]. The μc-Si:H material is a modification of silicon, which consists of microcrystallites separated by more or less extended amorphous regions. The volume parts of these phases and the grain size (from few up to some hundred nanometers) are strongly dependent on the deposition and process conditions used. Evidence of different film morphology has been found in samples deposited with different processes [3]. Therefore, this material is inhomogeneous and contains different phases, including their interfaces with different structural properties.

The proper description of the structural properties of this heterogeneous material is quite a complicated task. Among other factors, the influence of the amorphous-like interfaces between the grains leads to an additional complication in the picture of describing the device properties strictly as a superposition of a crystalline (c-Si) and amorphous (a-Si) phases corrected by a scattering coefficient. Also, the conic-like growth of the crystallites inside the amorphous phase leads to a p–i–n structure where the crystalline fraction is not uniform and increases from the p–i to the n–i interface [4].

In this study, we have analysed thin and entirely μc-Si:H p–i–n structures produced by closed-chamber chemical vapour deposition method [3] resulting in wide spectral range device with an enhanced sensitivity to the blue and near-infrared regions and a positive spectral response under forward bias. In order to gain insight into the transport mechanism, we have correlated the spectral responsivity and the internal collection efficiency with a detailed simulation analysis. A model, based on the band discontinuities near the grain boundaries, is presented and supported by numerical simulation.

2. Experimental procedures

2.1. Preparation and experiment

The detector consists of a ZnO-covered glass substrate, followed by a p^+-μc-Si:H/i-μc-Si:H/n^+-μc-SiH (μc-p–i–n) structure and Al top contact.

The dark and light current–voltage characteristics were performed at room temperature, using a tungsten–halogen

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[*] Corresponding author. Tel.: +351-1-8317181; fax: +351-1-8317114.
E-mail addresses: mv@isel.pt (M. Vieira), rschwarz@fisica.utl.pt (R. Schwarz).

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lamp (40 mWcm^{-2}). An open circuit voltage (V_{OC}) of 0.3 V and a short circuit current of 10 mA cm^{-2} were measured. The photocurrent, I_{ph}, for the different applied bias voltages (in the range of -1 to 1 V) and different light wavelength, λ (in the range of 300–1100 nm), were measured. The light was incident either through the glass ($\langle p \rangle$ side) or through the rear part of the photodiode ($\langle n \rangle$ side). The normalisation of I_{ph} to the number of photons onto the substrate yields the external collection efficiency, $Q(\lambda,V)$. The internal efficiency, $q(\lambda,V)$ was inferred by normalising $Q(\lambda,V)$ to its saturation value under strong reverse voltage, at any given wavelength, $q(\lambda,V) = -Q(\lambda,V)/Q(\lambda,V_{sat})$. This value was taken at $V_{bias} = -1$ V where we have assumed full collection. To suppress the dark current, all the measurements were performed using the lock-in technique.

2.2. Device modelling

Device modelling refers to the numerical simulation of semiconductor device physics to predict the electrical and optical behaviour. The µc-Si:H p–i–n device was simulated by using the ASCA simulator [5]. The problem of the material heterogeneity was approached by applying the heterostructure transport equations on the two-dimensional rectangular domain presented in Fig. 1.

The simulation takes into account the transverse dimension (perpendicular to the junction x) and one of the lateral ones (parallel to the junction y). This simulator can predict such parameters as carrier densities, transverse and lateral electric field profiles, potential distributions, dark characteristics, and photocurrents under different external conditions. The simulation of the illuminated condition has been made using the experimental absorption coefficients [4]. For example, we have used for the microcrystalline (amorphous) in the blue, red and infrared range, the following absorption coefficients: 4×10^4 (1×10^5 cm^{-1}), 1×10^4, (2×10^4 cm^{-1}) and 3×10^3 cm^{-1} (1×10^2 cm^{-1}), respectively.

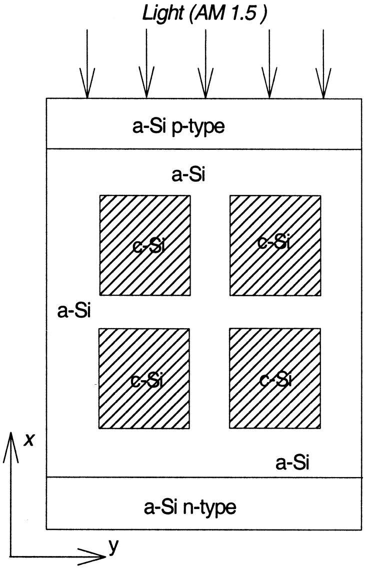

Fig. 1. Structure of the simulated rectangular domain.

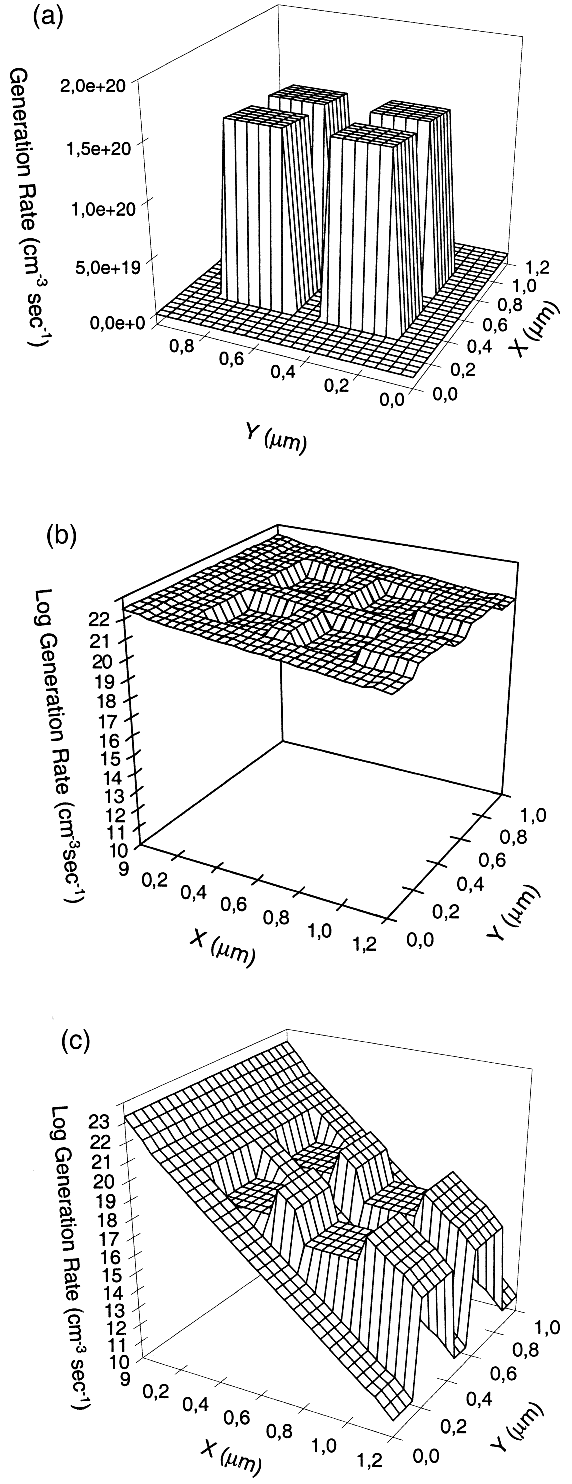

Fig. 2. The photo-generation rate profile within a microcrystalline p–i–n structure under (a) infrared, (b) red and (c) blue–violet illuminations.

3. Results

3.1. Current density and potential distributions

Fig. 2a,b and c depicts the photo-generation rate profiles for three energy values (1.55, 2.0 and 2.7 eV) with the light incoming from the ⟨p⟩ side. The generation rate depends on the wavelength and on the grain distribution. Under infrared illumination (Fig. 2a), the generation process is localised inside the grains; in the red range (Fig. 2b), the light is absorbed almost homogeneously along the structure; and in the blue–violet range (Fig. 2c), the generation is higher near the irradiated interface and in-between the grains.

It is important to notice that for the blue–violet radiation, each grain acts as a window and so, the high-energy

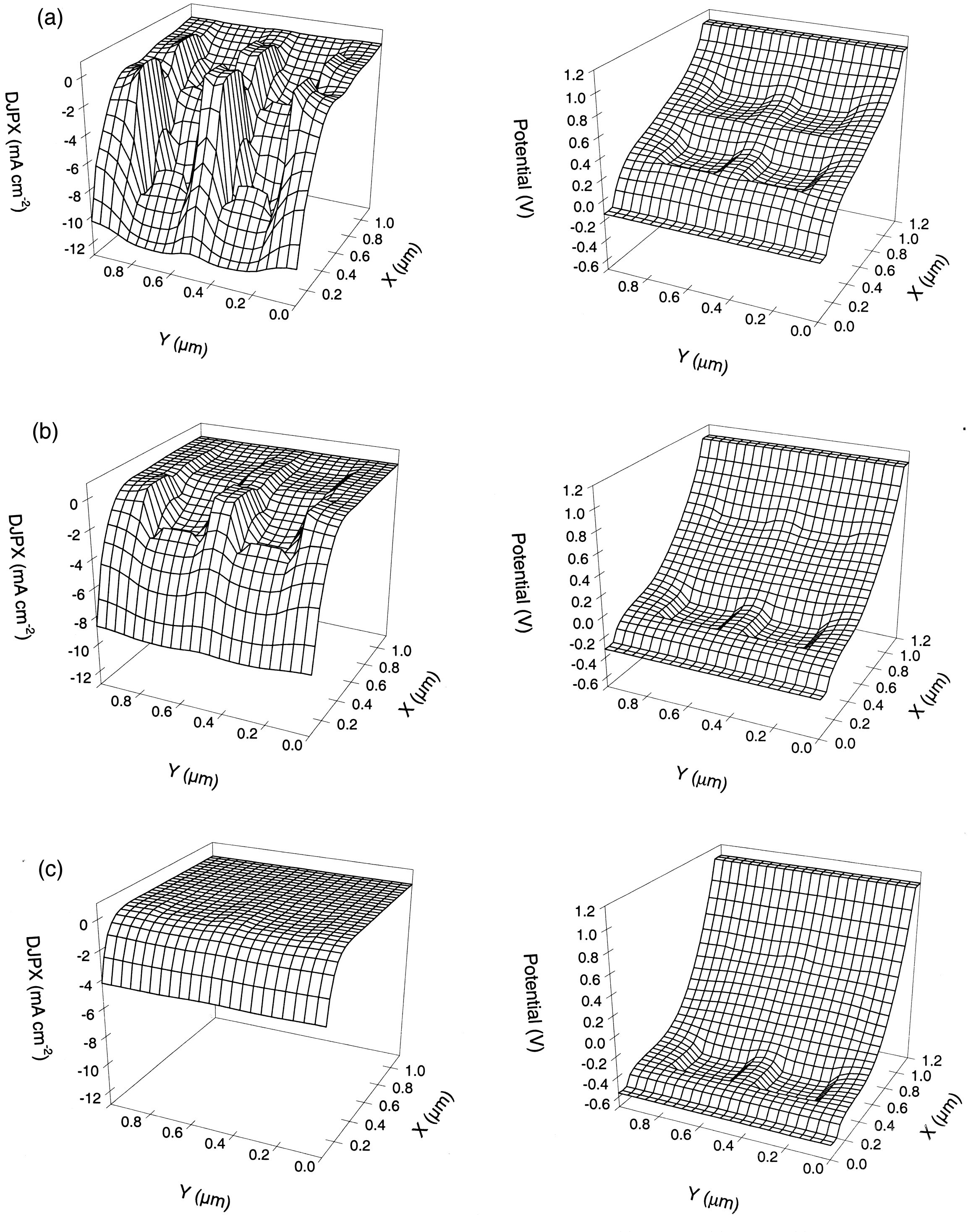

Fig. 3. Potential and current density profiles within μc-Si:H p–i–n device structure under (a) infrared, (b) red and (c) blue–violet illuminations.

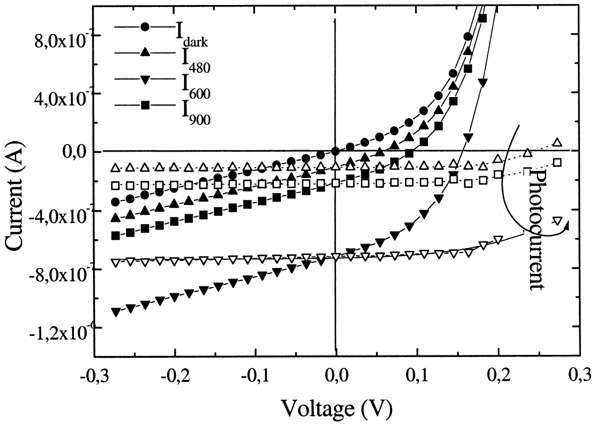

Fig. 4. Experimental current–voltage curves under dark and under different wavelength conditions (solid symbols), and photocurrent (open symbols) for a microcrystalline p–i–n structure, under n-side ilumination.

photons can be absorbed at higher distance than if the device were entirely amorphous. Since the generation process is not uniform, the photogenerated carriers tend to diffuse out towards the lower concentrations. Some of them are trapped at the grain boundaries, leading to a local distribution of the wavelength dependent electric field.

Fig. 3 shows the simulated hole current and the potential profile in open circuit condition for different irradiation wavelengths.

The total collected current is determined by the built-in electric field in superposition with the local fields. The lower is the photon energy, the higher is the influence of the local fields at the grain boundaries. In the low-energy range, the grains act as low potential regions; while, as the photon energy increases, the potential distribution smoothens hiding the heterogeneity ascribed to the microcrystalline nature.

In the infrared–red range (Fig. 3a,b), the percolation of carriers between grains is possible and a small photocurrent is expected even when an external bias higher than V_{OC} is applied. In the blue–violet range (Fig. 3c), the grains' position and/or size do not influence the current distribution. Small local fields can be observed only at the grain boundaries, which are near the p–i interface. The device behaves like a standard amorphous silicon p–i–n detector and no photocurrent is observed under open circuit condition.

3.2. The photocurrent

In Fig. 4, the experimental current–voltage curves in dark and under illumination, and the photocurrents are reported for different wavelengths.

Two distinct trends in the I–V characteristics were detected. The first one is seen for voltages below the open-circuit voltage, where the shunt resistance dominates, and a second trend shows up as an exponential increase of the current density with voltage. The shift of threshold voltage (which is taken as the open-circuit voltage) is ascribed to the changes in series resistance under different wavelength illumination. It is important to notice that under "blue" light, a transition from primary to secondary photocurrent is observed, while under red and infrared irradiation — in the voltage range analysed — the photocurrent is always negative.

3.3. Spectral response and collection efficiency

The conic-like growth of the crystallites inside the amorphous phase leads to a p–i–n structure where the crystalline fraction is not uniform and increases from the p–i to the i–n interface. The grains grow mainly in the transverse direction with almost no boundary from the bottom (⟨p⟩ side) to the top (⟨n⟩ side). In-between the grains, an amorphous or a lattice-mismatched phase exists dependent on the grain distance [4].

To average the contribution from the amorphous, the microcrystalline, and the lattice-mismatched phases, we have irradiated the device through the ⟨p⟩ and ⟨n⟩ sides, respectively, and analysed the spectral response [6] and the collection efficiency. In Fig. 5a and b, the responsivity curves, normalised to their maximum, are displayed for different applied voltages with the light entering from the ⟨p⟩ and ⟨n⟩ sides, respectively.

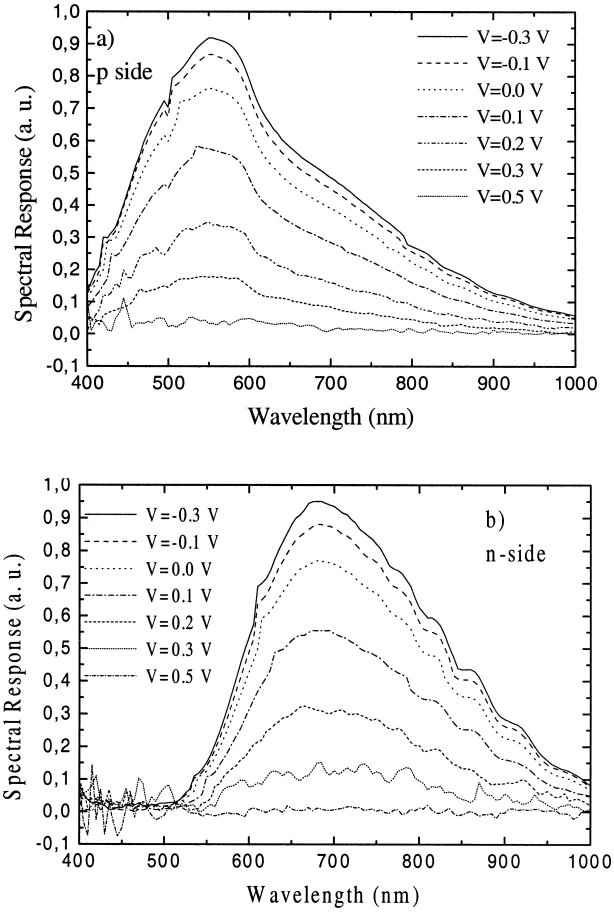

Fig. 5. Measured spectral photoresponse curves under different bias voltages under (a) ⟨p⟩ side illumination, and (b) ⟨n⟩ side illumination.

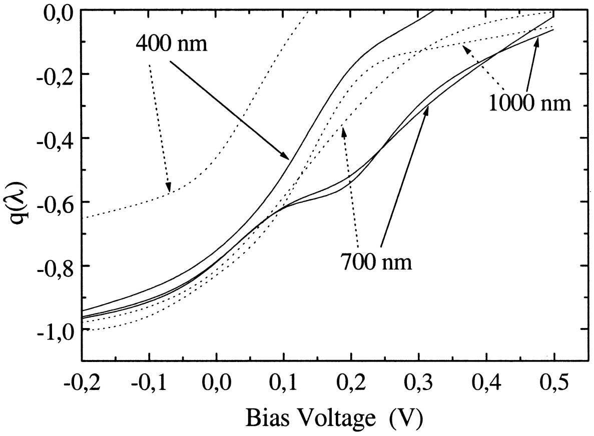

Fig. 6. Measured internal efficiency as a function of the applied bias for different wavelength under ⟨p⟩ side illumination (solid line), and ⟨n⟩ side illumination (dotted line).

Results show that the spectral response depends on the illuminated side. Under front illumination (Fig. 5a), the spectral response is extended beyond 1000 nm and reaches maximum value near 500 nm. If the light is incident through the rear part of the diode (Fig. 5b), the infrared response is increased and the maximum is shifted towards the near-infrared with a rejection of the blue spectrum.

Fig. 6 depicts the internal collection efficiency as a function of the applied bias for different wavelengths under ⟨p⟩ and ⟨n⟩ sides illumination.

The internal collection depends not only on the energy range but also on the illumination side. Under irradiation from both sides, the internal collection characteristics have an atypical shape. $q(\lambda,V)$ is high for $V < V_{OC}$ (higher under ⟨n⟩-side illumination), has a steep decrease near V_{OC} (higher under ⟨n⟩-side illumination) and flattens for $V > V_{OC}$.

4. Discussion

4.1. The transport mechanism

Combining the experimental results with the numerical simulations and taking into account published results [6,7], we can give a qualitative explanation of the device operation by invoking preferential transport paths through the crystalline, the amorphous, and the lattice-mismatch regions. Those preferential paths change depending on the wavelength of the absorbed light and on the bias voltage.

In the infrared range, the carriers generated inside the crystallites flow along the grains mainly by diffusion in transverse direction. This is because the potential profile is flat inside the grains, as seen in Fig. 3a. As the wavelength decreases, the grains become more and more transparent to the optical radiation, and the potential profile approaches the shape of a purely amorphous structure. So, the carriers generated inside the intermediate disordered regions flow along the amorphous phase driven by the built-in field. Since, as we have explained above, the carrier density is high inside the grains, it is crucial to know which type of carriers, electrons, or holes, can easily cross the amorphous and lattice-mismatch regions. This will depend on the carrier concentration gradients for diffusion and on the grain boundary field strength for drift processes. The direction of such boundary fields and their absolute values will depend strongly on the ratio between valence and conduction band offsets and is obviously not accessible in a real sample. As an overall effect, the grain boundary fields will allow one type of carrier to use preferentially the highly conduction path through the grains. The other type of carriers may still be collected after transport through the disordered regions.

Under reverse bias, the junction electrical field dominates the carrier collection and the photocurrent is an average of all the contributions. As the forward bias increases, the junction electric field decreases, and the transport will change from a drift-controlled to a diffusion-limited process. This changeover is defining a turn-off point, which depends on the irradiation wavelength and on the spatial distribution of the grains, as seen in Fig. 6. Such a retarding effect was also seen in amorphous silicon solar cells and explained by an increased density of trap states near the p- and i-layers [8]. In our case, such a highly defective region could correspond to the initially amorphous part of the microcrystalline i-layer. The turn-off point is not shifted to higher voltages in the case of ⟨n⟩-side illumination, since most of the collected carriers are originated from regions other than the p–i interface for all wavelengths.

The infrared light is the only light absorbed in the crystalline part of the detector (Fig. 2) so, even for applied bias higher than V_{OC}, the device delivers current (Fig. 6) since the crystalline phase functions as a photodetector and the amorphous one as impedance.

5. Conclusions

A qualitative model based on three main transport paths is proposed to explain the collection mechanism inside the microcrystalline p–i–n photodetectors. The influence of the local electric fields is strong enough to channel the flow of one type of carriers, preferentially through paths including the grains.

Numerical simulations prove to be a helpful tool in visualising the origin of those processes, which depend on the applied voltage, and the wavelength of the absorbed light.

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Biographies

Manuela Vieria was born in Lisbon, Portugal in 1951. She was earned a degree in Physics from the University of Lisbon in 1974. In 1986, she received the Master of Science in Solid State Physics-Microelectronic from the New University of Lisbon. At that time, she became Auxiliary Professor of Semiconductor and Microelectronics in ISEL, Lisbon, where she is currently a Coordinator Professor in Semiconductor/Electronics and the President of the Department of Electronics and Communications. In 1984, she became member of the Center of Excellence for Microelectronics and Optoelectronics Processes — UNINOVA, Portugal. In 1993, she received her PhD in Semiconductor Materials from the New University of Lisbon. Currently, she is the head of the Group In Applied Research in Microelectronic Optoelectronic and Sensors — GIAMOS/ISEL in Lisbon, Portugal. Dr. M. Vieira has authored several scientific papers and has more than 12 years of experience in the field of thin films and devices. Her research activities have been mainly related to the transient analysis and characterization of the transport properties of the semiconductor materials and device characterization.

Alessandro Fantoni was born in Rome, Italy in 1966. He received his degree in Mathematics in the Università Degli Studi di Camerino, Italy, in 1992. Since March 1993, he has been working as investigator in UNINOVA–CEMOP (Campus of FTC–UNL), Lisbon Portugal, in the field of mathematical modeling and computer simulation applied to amorphous and microcrystalline semiconductors. In 1999, he received his PhD degree in Materials Science and Engineering from the Universidade Nova de Lisboa, Faculdade de Ciências e Tecnologia in the field of Microelectronics and Optoelectronics. Since 1999, he has been teaching mathematics in the Electronics Department of ISEL (Superior Engineering Institute of Lisbon). His main research interest is software development for simulation of amorphous semiconductor properties.

Miguel Fernandes was born in Portugal in 1970. In 1993, he became a researcher in the Center of Excellence for Microelectronics and Optoelectronics Processes — UNINOVA, Lisbon Portugal. He graduated with a degree in Physics and Materials Engineering the New University of Lisbon in 1995. Currently, he is an Assistant Professor in the Electronics Department of ISEL, Lisbon, Portugal, and investigator for the Applied Research in Microelectronic Optoelectronic and Sensors-GIAMOS in the same institution.

António Maçarico was born in Evora, Portugal in 1960. He received his degree in Physics and Materials Engineering from the New University of Lisbon in 1988. Between 1983 and 1987, he worked as a collaborator in the Molecular Physics Center Line 6 of INIC (National Institute of Scientific Research), Portugal, where his work was devoted to characterization and production of amorphous silicon. In 1989, he joined PORTSOL (TUDOR group) and was involved in a project of technology transfer between university and industry or the industrial production of amorphous solar cells. From 1991 to 1997, he worked as researcher at UNINOVA, Lisbon, Portugal. Currently, he is Adjunct Professor in ISEL, Lisbon, Portugal.

Reinhard Schwarz was born in Groβköris, Germany, in 1950. He received his degree in Physics and Mathematics from the University of Stuttgart, Germany, in 1977. He joined the department Physics in Neuchâtel University, Switzerland, where he taught, and received his PhD in 1982. Soon thereafter, he became a scientific collaborator in the Institute of Microtechnology, University of Neuchâtel, Switzerland, until 1983 when he joined the group of Prof. S. Wagner in the Department of Electrical Engineering, Princeton University, USA. Later, he joined the Physics Department E16 of the Technische Universität München, Germany until 1996. Since then, he has been teaching as Visiting Professor in the Physics Department in the Instituto Superior Técnico, Lisbon, Portugal and Coordinator Professor in Electronics Department of Instituto Superior de Engenharia de Lisboa, Portugal.