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Bias-dependent photocurrent collection in p–i–n a-Si:H/SiC:H heterojunction

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Abstract

A series of large area single layers and glass/ZnO:Al/p(Si_xC_{1-x}:H)/i(Si:H)/n(Si_xC_{1-x}:H)/Al ($0 < x < 1$) heterojunction cells were produced by plasma-enhanced chemical vapour deposition (PE-CVD) at low temperature. Junction properties, carrier transport and photogeneration are investigated from dark and illuminated current–voltage (*J–V*) and capacitance–voltage (*C–V*) characteristics. For the heterojunction cells atypical *J–V* characteristics under different illumination conditions are observed leading to poor fill factors. High series resistances around $10^6\ \Omega$ are also measured. These experimental results were used as a basis for the numerical simulation of the energy band diagram, and the electrical field distribution of the structures. Further comparison with the sensor performance gave satisfactory agreement. Results show that the conduction band offset is the most limiting parameter for the optimal collection of the photogenerated carriers. As the optical gap increases and the conductivity of the doped layers decreases, the transport mechanism changes from a drift to a diffusion-limited process.

Keywords: Optical bias; Heterostructures; Optoelectronic properties; Numerical simulation

1. Introduction

The a-SiC:H/a-Si:H heterojunctions are often used in amorphous photodiodes due to the wide band gap of the a-SiC:H since the probability of carrier injection depends on the potential barrier height and width. The nature of the a-SiC:H/a-Si:H heterojunction leads to the accumulation of photogenerated carriers which gives rise to a light induced barrier modulation under nonuniform illumination. This effect is the basis of the laser scanned photodiode (LSP) image sensor [1]. The use of a back layer based on Si–SiC arises from the fact that this structure allows a better confinement of the carrier generated by the scanner in the bright regions.

Our recent works on a-Si:H p–i–n LSD image sensors have shown that replacing the n-type a-SiH layer with a highly resistive a-SiC:H results in a remarkable improvement in the spatial resolution [2] which was ascribed to an enhancement of the electric field modulation across the depletion region that prevents the carriers to smear out in the lateral direction [3], as well as to a reduction of the diffusion length of carriers in SiC layers.

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The aim of this work is to describe the results of experiments as well as to discuss the usefulness of the a-SiC alloy materials for the improvement of the sensor performance. The efforts were focused mainly on doped n- and p-type layer at high and low doping levels with and without carbon, as well as intrinsic layers. A systematic research on the optoelectronic properties of the layers and related devices under dark and different light illumination conditions was performed to understand its role on the output performance of the a-SiC:H based p–i–n image transducer.

2. Experimental details and characterisation

Large area (4 cm × 4 cm) amorphous layers and p–i–n structures in glass/ZnO:Al/p(Si:H)/i(Si:H)/n(Si_xC_{1-x}:H)/Al assembly were produced. All layers were deposited by plasma-enhanced chemical vapour deposition (PE-CVD), at a 13.56 MHz radio frequency [4]. The deposition pressure was 200 mTorr, the substrate temperature was held at 150 °C and the rf power was 4 W. Intrinsic and doped a-SiC:H films were deposited on Corning glass AF45, under the same conditions of the cells, in order to infer the electro-optical properties of each single layer. The deposition conditions of all i-layers were kept constant while they varied in the n- and

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Table 1
Deposition parameters of the p–i–n structures

Sensor code	Layers	SiH_4 (sccm)	H_2 (sccm)	PH_3 (sccm)	B_2H_6 (sccm)	CH_4 (sccm)	Thickness (Å)
#M006291/2	p	11.96	–	–	0.04	0	500
	i	20.00	10.00	–	–	–	5000/2500
	n	11.98	–	0.02	–	0	500
#M006301/2	p	11.96	–	–	0.04	0	500
	i	20.00	10.00	–	–	–	5000/2500
	n	11.98	–	0.02	–	20.00	500
#M007192	p	11.96	–	–	0.04	20.00	500
	i	20.00	10.00	–	–	–	5000
	n	11.98	–	0.02	–	20.00	500

p-layers as reported in Table 1. Sputtering and thermal evaporation techniques were used to produce the front and back contacts. The front contact ZnO:Al is 300 nm thick and has a transmissivity of approximately 80% from 425 to 700 nm and a resistivity around $9 \times 10^{-4}\ \Omega$ cm.

A preliminary electrical and optical characterisation of the films was carried out by measuring the electrical conductivity in the coplanar direction and by obtaining the absorption spectra from transmission and reflection measurements in the UV–VIS–NIR range. These results were also complemented with constant photocurrent measurements [5], to evaluate the Urbach energy.

The dark, σ_d, and photoconductivity, σ_{ph}, under AM1.5 (100 mW/cm^2), the activation energy, ΔE, the optical Tauc gap, E_{op}, and the Urbach energy, E_{ur}, measured for each single layer are summarised in Table 2.

Junction properties, carrier transport and photogeneration are investigated from dark and illuminated current–voltage (*J–V*) and capacitance–voltage (*C–V*) measurements at room temperature. *J–V* measurements were performed at different light intensity conditions and under an AM1.5 simulator.

The *J–V* characteristics of a p–i–n device under illumination can be approximately described by using the transport equation of an ideal p–n junction [6,7]. The measured current is given by

$$J(V) = J_D(V - JR_s) - J_L(V - JR_s) \tag{1}$$

where J_D and J_L are the diode current and the photocurrent corrected for series resistance, R_s.

$$J_D = J_0\left[\exp\left(\frac{q(V - JR_s)}{nKT}\right) - 1\right] \tag{2}$$

where n is the ideality factor and $V - JR_s$ is the voltage at the junction of an ideal diode corrected for series resistance. J_0 is the reverse saturation current. Assuming that the photocurrent is much lower than the dark current, the derivative dV/dJ from Eq. (1) is given by

$$\frac{dV}{dJ} = R_s + \left[\left(\frac{nkT}{q}\right)\frac{1}{J_D(V)}\right] \tag{3}$$

To obtain n, R_s and J_0 directly from the experimental data we used the dark *J–V* characteristics.

When dV/dJ is plotted against $1/J_D$, the slope is nkT/q and the intercept is R_s. Using the value of R_s from the intercept a graph of the log J_D as a function of $V - JR_s$ yields a straight line with slope q/nkT and intercepts J_0. Key cell characteristics such as open-circuit voltage V_{OC}, short-circuit current J_{SC}, n factor and the reverse saturation current J_0 are listed in Table 3.

Capacitance–voltage measurements were carried out with a 104 Hz/20 mV test signal, using a lock-in amplifier to measure real and imaginary part of ac impedance. Sample capacitance and conductance is calculated from the measured values, assuming a parallel *RC* model [8]. The use of

Table 2
Optoelectronic properties of the individual layers

Sensor code	Layers	σ_d (Ω^{-1} cm^{-1})	ΔE (eV)	E_{op} (eV)	σ_{ph}/σ_d	E_{ur} (meV)
#M006291	p	8.2×10^{-7}	0.499	1.80	7.3	140
	i	7.6×10^{-11}	0.739	1.79	7.1×10^4	72
	n	7.8×10^{-7}	0.426	1.82	1.2	100
#M006301	p	8.2×10^{-7}	0.499	1.80	7.3	140
	i	7.6×10^{-11}	0.739	1.79	7.1×10^4	72
	n	1.9×10^{-12}	0.834	2.10	21	200
#M007192	p	2.5×10^{-9}	0.649	2.06	4.5	–
	i	7.6×10^{-11}	0.739	1.79	7.1×10^4	72
	n	1.9×10^{-12}	0.834	2.10	21	200

Table 3
Series resistance and key cell characteristics of each sensor

Sensor code	R_s (Ω/cm^2)	V_{OC} (V)	J_{SC} (mA/cm^2)	J_0 (mA/cm^2)	n
#M006291	1.2×10^3	0.84	2.12	6.0×10^{-12}	1.8
#M006301	4.0×10^5	0.70	0.20	1.0×10^{-10}	2.9
#M007192	7.0×10^5	0.59	0.04	1.5×10^{-10}	3.5

such a low frequency to perform the measurements was due to the high value of the series resistance.

3. Results and discussion

3.1. Individual layers

In Fig. 1 the conductivity is shown as a function of 1/*T*, and Fig. 2 shows the transmittance dependence with energy for the single layers used to produce the sensor devices.

The low doping levels are responsible for the high ΔE values and for the low σ_d of the doped layers. As expected the dark conductivities of the doped layers decreases (Fig. 1) and optical gap increases (Fig. 2) with the incorporation of carbon (see Tables 1 and 2). The shift of the absorption edge shown in Fig. 2 is due to the carbon doping.

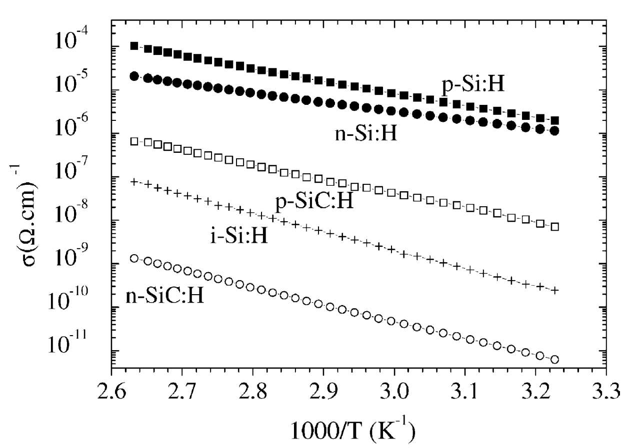

Fig. 1. Dark conductivity as a function of 1/*T*.

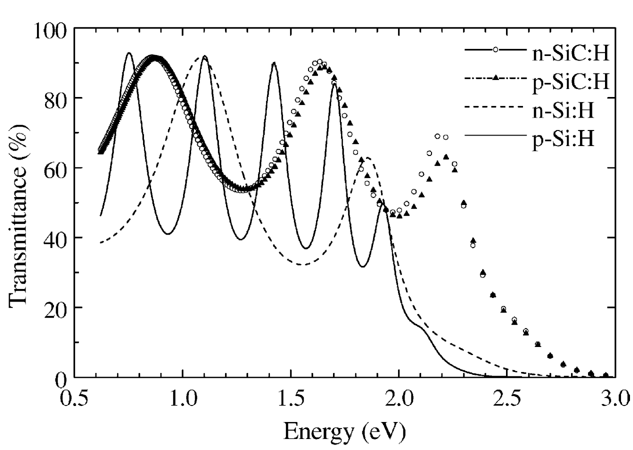

Fig. 2. Transmittance as a function of the energy.

3.2. The J–V characteristics

In Fig. 3 the *J–V* characteristics in dark (a) and under AM1.5 illumination (b) are displayed.

As the sensitive area is very large, about 4 cm × 4 cm, and the diffusion length in a-Si is about 1 μm, the corrections due to dimensions of outward depletion region and to lateral diffusion are negligible.

In dark, the reverse *J–V* curves present a large current change and, in the voltage range analysed, no saturation point is observed (Fig. 3a). Under illumination and reverse mode (Fig. 3b) for the heterojunctions (#M006301, #M007192) the photocurrent is bias dependent and the reverse gain suggests carrier injection from the doping layers to the i-layer. Data show that J_0 and n are higher and V_{OC} and J_{SC} are lower in the heterojunction than in the homojunction (#M006291). The higher series resistances and the lower V_{OC} and J_{SC} were measured when both a-SiC:H based doped layers were used (see Table 3). In these conditions the leakage current is too small to be evaluated from the experimental curves.

We used a device simulation program AMPS-1D to analyse the charge carrier transport in the investigated structures [9]. Typical values of band tail and gap state parameters for amorphous materials were used. The doping level was adjusted in order to obtain approximately the same conductivity of the layers as in the tested samples. In the a-SiC:H film the optical band gap of 2.1 eV was chosen in compliance with the obtained experimental values (see Table 1). As there is no information on the band offsets, we used the simplest model with the band discontinuities equally distributed over the valence and the conduction band offsets ($\Delta E_v = \Delta E_c = 0.15\,\text{eV}$). The standard daylight spectrum was used to simulate the device illumination. Detailed simulation studies have been carried out at applied bias voltage in the range of −1 to 1 V and under different light power density, Φ_L.

Fig. 4a displays the simulated and experimental *J–V* characteristics for the p–i–n homo- and heterojunctions under AM1.5 illumination. Fig. 4b shows for a heterostructure (#M007192) the experimental and the simulated *J–V* characteristics in dark and at different illumination conditions.

A good agreement between simulated and experimental data is achieved, as can be seen from the shape of both curves, and by the short-circuit current and by the open-circuit voltage values. This shows that the set of input parameters chosen for the simulation model are reasonable. In the heterostructures both the experimental and the simulated *J–V* characteristics show a non-exponential dependence at forward bias higher than 0.4 V. Under illumination, an S-shaped *J–V* dependence is observed for $\Phi_L > 10^{-5}$ W/cm^2. It is interesting to notice that for forward bias higher than

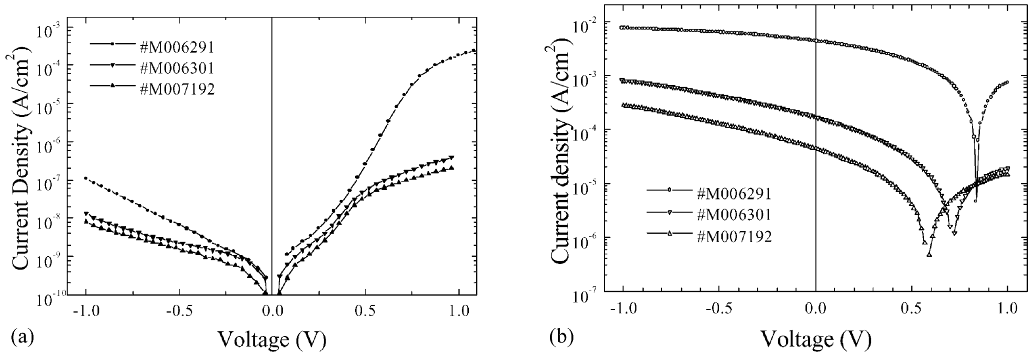

Fig. 3. *J–V* characteristics in (a) dark and (b) under AM1.5 illumination.

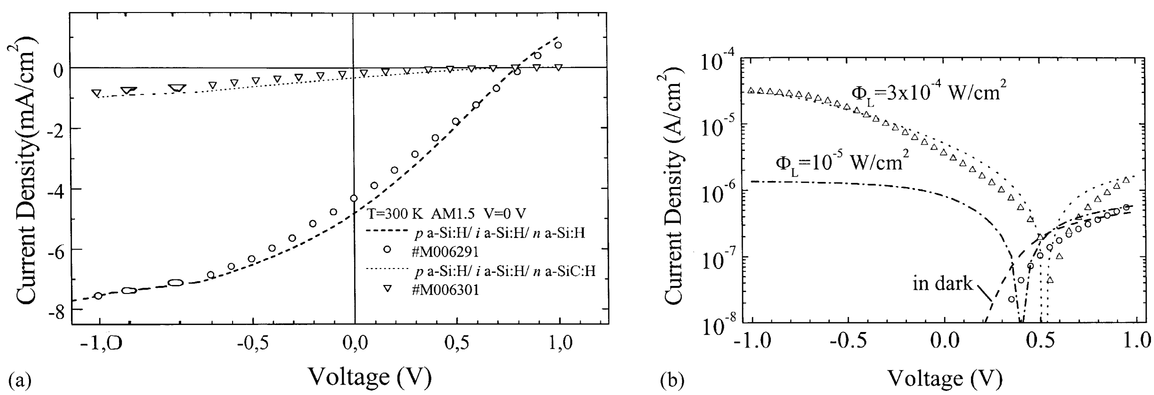

Fig. 4. (a) Comparison between simulated and experimental *J–V* characteristics for the p–i–n homo- and heterojunctions under AM1.5 illumination and (b) measured (symbols) and simulated (dashed lines) *J–V* characteristics at 300 K for the a-Si:H p–i–n heterostructure.

0.6 V, the current under illumination exceeds the dark current (see Fig. 3).

3.3. The capacitance–voltage characteristics

Fig. 5a displays the *C–V* characteristics in dark and under different light intensities, Φ_L, for the sample #M006301. In Fig. 5b the capacitance dependence with Φ_L without any bias voltage and the corresponding calculated depletion widths are shown. Results show that the capacitance increases and saturates at voltage values that depend on the light intensity. The increase on the capacitance is due to the shrinking of the depletion region width, *w*, under illumination. In dark conditions and with no bias voltage the device is fully depleted, $w \cong 360$ nm, while under illumination (530 nm; 20 mW/cm^2), *w* decreases to values around 80 nm suggesting that even at zero bias and low optical bias the depletion region quenches to its minimum value and the current collection

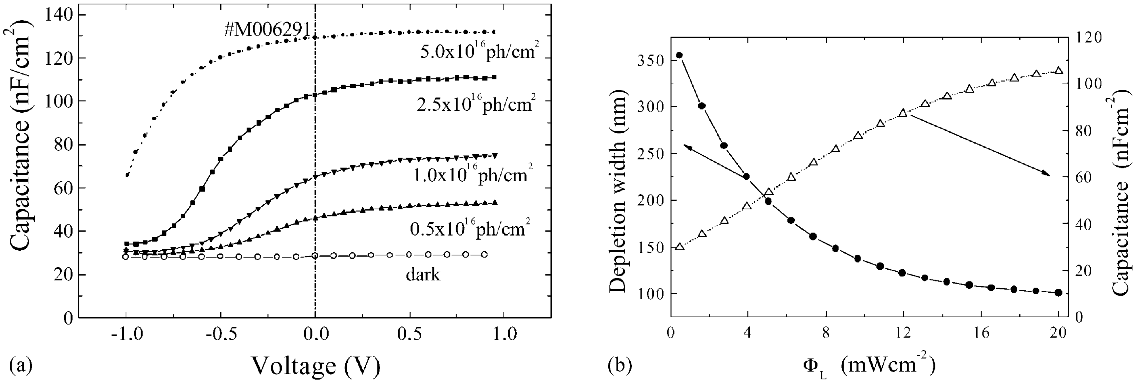

Fig. 5. (a) *C–V* characteristic under different light intensities and (b) capacitance and depletion width dependence with Φ_L.

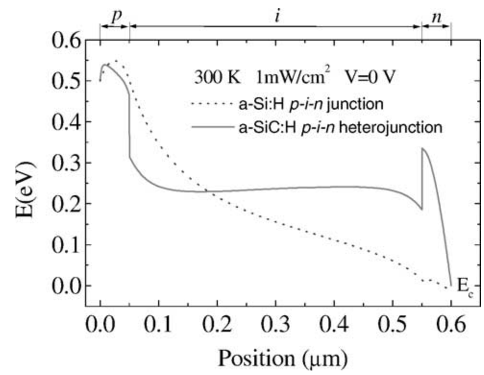

Fig. 6. Conduction band diagram of an a-Si:H p–i–n homojunction and a heterojunction under short-circuit condition.

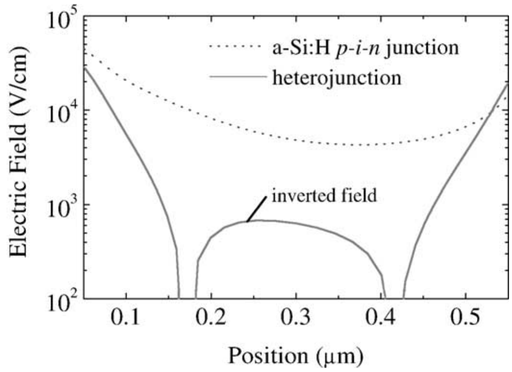

Fig. 7. Electric field profile within a homojunction (dotted line) and a heterojunction (solid line) in short-circuit condition.

becomes diffusion controlled instead of field aided as it is commonly expected in p–i–n homostructures. This turning point in the conduction mechanism is the basis for using p–i–n heterostructures with high resistive doped layers as LSP image detectors [1].

3.4. Transport mechanism

The conduction band diagram and electric field profile for the diodes under short-circuit condition at $\Phi_L = 1$ mW/cm^2 are displayed in Figs. 6 and 7, respectively.

As the light intensity increases, the potential drop across the a-SiC:H n-layer increases (Fig. 6) leading to the inversion of electric field strength in the bulk of the i-layer (Fig. 7). In the homojunction the band bending is different. Here the potential drop across the n- and p-layers is insignificant and the electric field remains high across undoped region. This inversion prevents carrier transport towards the contact, leading to a reduction of the photocurrent under illumination.

In Fig. 8a the electron and hole current density profiles within the homojunction are shown and in Fig. 8b the electrons current density in the i-layer of the heterojunction separated in drift and diffusion part is presented. Both structures are under short-circuit condition and the light power density was 1 mW/cm^2.

For the homojunction both hole and electron photocurrents are negative and as expected the transport mechanism is drift dominated due to high electric field strength in the active region. Within the heterojunction the current profile shows a significant change in the drift-diffusion balance when compared with the homostructure. In order to analyse the transport mechanism the electron current density J_n is separated in both drift J_n^{drift} and diffusion $J_n^{diffusion}$ components. In the inverted field region (see Fig. 7) the diffusion component of electron current is dominant, however, in the regions close to both p–i and i–n interfaces the transport process remains drift dominated. In this situation, the recombination rate is high and collection efficiency is poor.

Under illumination the SiC:H doped layers will work as blocking layers preventing electrons and holes from being injected into the i-layer. Here, the low field region is not enough to sweep the photocarriers to the contacts before their recombination, which leads to a low collection. This field-dependent collection reduces the photocurrent at forward bias leading to atypical *J*–*V* characteristics and poor fill factors (Fig. 4a). As the light intensity increases the collected current seems to present a voltage-dependent shunt loss (Fig. 5b). The transport mechanism in dark conditions depends almost exclusively on field-aided drift while under illumination it will depend mainly on the diffusion of minority carriers to collect the photocurrent.

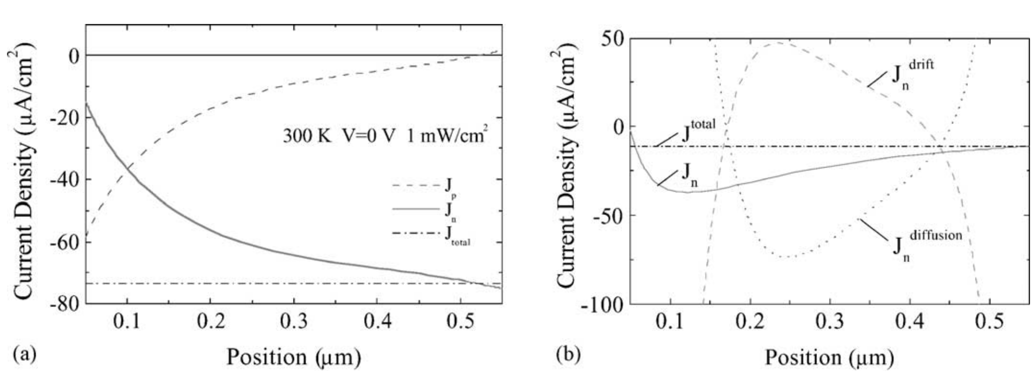

Fig. 8. Electron and hole current profiles in short-circuit condition within a homojunction (a) and a heterojunction (b). The light power density was 1 mW/cm^2.

4. Conclusions

Considerations about band misalignment, modified electrical field profiles and drift-diffusion transport mechanism were used to explain the atypical shapes of the light *J–V* characteristics and the quenching of the depletion regions under illumination in p–i–n a-SiC:H based heterostructures.

The transport mechanism in dark conditions depends almost exclusively on field-aided drift while under illumination it will depend mainly on the diffusion of carriers. The turning point in the conduction mechanism depends on the light intensity and on the nature of the doped layers when a p(SiC:H)/i(Si:H)/n(SiC:H) configuration is used. This dependence is the basis of the use p–i–n heterostructures with high resistive doped layers as LSP image detectors.

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Biographies

P. Louro was born in Portugal in 1967. In 1990 she became researcher in EID (a company of research and development in the field of electronics), Lisbon, Portugal, in the Department of Optoelectronics. She graduated in physics from the Faculty of Sciences, University of Lisbon in 1990. In 1995 she received her MS in material engineering from New University of Lisbon. Currently she is assistant professor in the Electronics Department of ISEL, Lisbon, Portugal, where she teaches electronic and semiconductor physics. Her main research interest is in the field of amorphous semiconductor thin films.

M. Vieira was born in Lisbon, Portugal in 1951. She graduated in physics from Faculty of Sciences, University of Lisbon in 1974. In 1986 she received her MS in solid-state physics microelectronics from New University of Lisbon. At that time she became auxiliary professor of semiconductor and microelectronics in ISEL, Lisbon where she is now coordinator professor in semiconductor/electronics and president of the Department of Electronics and Communications. In 1984 she became member of Center of Excellence for Microelectronics and Optoelectronics Processes (UNINOVA), Portugal. In 1993 she received her PhD in semiconductor materials from 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 several scientific papers to her credit and 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 characterisation of the transport properties of the semiconductor materials and device characterisation.

Yu. Vygranenko was born in Ukraine in 1963. He received his degree in physics by the Chernovtsy University, Ukraine in 1985. Between 1985 and 1987 he worked as engineer at the optoelectronics device plant "Quartz", Ukraine. Later he became scientific collaborator in the Chernovtsy Department of the Institute of Materials Science Problems, where his research work was related to the physics and technology of the IV–VI narrow-gap semiconductors. In 1997 he received his PhD in physics from the Chernovtsy University. Currently he works as researcher in ISEL, Lisbon, Portugal.

M. Fernandes was born in Portugal in 1970. In 1993 he became researcher in the Center of Excellence for Microelectronics and Optoelectronics Processes (UNINOVA), Lisbon, Portugal. He graduated in physics and materials engineering from the Faculty of Sciences and Technology, New University of Lisbon in 1995. Currently he is assistant professor in Electronics Department of ISEL, Lisbon, Portugal and investigator in the Group in Applied Research in Microelectronic Optoelectronic and Sensors (GIAMOS/ISEL) in the same institution.

R. Schwarz was born in Großköris, Germany in 1950. He received his degree in physics and mathematics from the University of Stuttgart, Germany in 1977. He joined the Department of Physics in Neuchâtel University, Switzerland where he was teacher and where he also received his PhD in 1982. After this he became 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 Technische Universität, München, Germany until 1996. Since then he teaches as invited professor in the Physics Department in Instituto Superior Técnico, Lisbon, Portugal and coordinator professor in Electronics Department of Instituto Superior de Engenharia de Lisboa, Portugal.

M. Schubert was born in Germany in 1958. He got his diploma in electrical engineering (Dipl-Ing) from the Faculty of Electrical Engineering of the University of Stuttgart in 1985. The same year he joined the Institute of Physical Electronics in the University of Stuttgart as a research associate in the amorphous silicon group. The main working topic was on materials research for thin film solar cells. In 1992 he received his PhD in electrical engineering (Dr-Ing) from the Faculty of Electrical Engineering of the University of Stuttgart. From 1992 to 1996 he taught in the University of Ulm (Germany) as professor of energy conversion and storage. Since 1996 he is group leader in "thin film sensors" at Institute of Physical Electronics, Stuttgart University, managing various research programs on thin film sensors and solar cells. Currently he is associate director of Institute of Physical Electronics at Stuttgart University (Germany).