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Thin film sensors produced at low temperature: a trade-off between carbon composition and spectral response

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A series of large area single layers and homo and heterojunction cells in the assembly glass/ZnO:Al/p (Si_xC_{1x}:H)/i (Si:H)/n (Si_xC_{1-x}:H)/Al ($0<x<1$) were produced by PECVD at low temperature. Junction properties, carrier transport and photogeneration are investigated from dark and illuminated current-voltage characteristics, and spectral response measurements in dark and under different illumination conditions. For the heterojunction cells atypical J-V characteristics under different illumination conditions are observed leading to poor fill factors. High series resistances around $10^6\Omega$ were measured. In these structures it was observed that the responsivity decreases with the increase of the light bias intensity. The homojunction presents the typical behaviour of a non optimized p-i-n cell and the responsivity varies only slightly with the light bias conditions.

Keywords: Heterojunctions; spectral sensitivity; thin films.

En este trabajo se utiliza un conjunto de homo y heterouniones (con estructura vidrio/ZnO:Al/p (Si_xC_{1x}:H)/i (Si:H)/n (Si_xC_{1-x}:H)/Al ($0<x<1$)) y de películas delgadas depositadas en gran área por PE-CVD a baja temperatura. Se estudian las propiedades de las uniones, el transporte de portadores y la fotogeneración a través de la medida de las características corriente–tensión en el oscuro y bajo iluminación, así como de medidas de repuesta espectral en el oscuro y bajo diferentes condiciones de iluminación. En las heterouniones se observan características corriente-tensión (bajo iluminación) de forma atípica que dan origen a bajos *full-factors*. Se observan igualmente elevados valores de resistencia serie de la orden de $10^6\Omega$. En estas estructuras se ha observado una aminoración de la respuesta ante un incremento de la intensidad luminosa. La homounión presenta un comportamiento típico de una célula p-i-n no optimizada en que la respuesta cambia ligeramente con las condiciones de iluminación.

Descriptores: Heterojunciones; sensibilidad espectral; peliculas finas.

PACS: 73.40.Lq; 73.40.Cg

1. Introduction

Preliminary studies on the use of glass/ZnO:Al/pin aSi:H/Al structures as image sensors have recently shown its potential capability [1]. The improvement of the device characteristics can be achieved by applying a wide band gap a-$Si_{1-x}C_x$:H as interface material to control carrier collection. By using this blocking layer the photocurrent becomes dependent on the height and width of the potential barrier [2]. This optimization demands a full understanding of the transport mechanism in p-i-n a-Si:H/a-SiC:H heterojunctions on the grounds of the physical properties of each layer.

This work concerns the electrical, optical characterisation of the a-$Si_{1-x}C_x$:H films deposited by PE-CVD. The efforts were focused mainly on doped n and ptype 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 device.

TABLE I. 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 (nm)
#M006291/2	P	11.96	—	—	0.04	0	50
	i	20.00	10	—	—	—	500/250
	n	11.98	—	0.02	—	0	50
#M006301/2	P	11.96	—	—	0.04	0	50
	i	20.00	10	—	—	—	500/250
	n	11.98	–	0.02	—	20	50
#M007192	p	11.96	—	—	0.04	20	50
	i	20.00	10	—	—	—	500
	n	11.98	—	0.02	—	20	50

2. Experimental details and characterization

Large area (4×4 cm^2) amorphous single layers and pin structures in the assembly glass/ZnO:Al/p (Si:H)/i (Si:H)/n (Si_xC_{1-x}:H)/Al were produced. All layers were deposited by Plasma Enhanced Chemical Vapor Deposition (PE-CVD), at a 13.56 MHz radio frequency [3]. The deposition pressure was 200 mTorr, the substrate temperature was held at 150°C and the rf-power was 4 W. Intrinsic and doped aSiC: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 gas fluxes during the deposition are reported in Table I. They were kept constant in all the i-layer and have been changed in the doped layers.

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 nm to 700 nm and a resistivity around 9×10^4 Ω cm.

Optical characterization of the single layers was performed with UV/VIS/NIR spectrophotometry to measure the thickness of the films, the optical gap, E_{op} and the refractive index of the material, as well as to estimate the absorption coefficient. These results were also complemented with CPM [4] measurements to infer the subgap absorption and the Urbach energy, E_{ur}.

Electrical characterization consisted mainly on the measurement of the conductivity, σ_d, versus temperature, of the photoconductivity, σ_{ph}, under AM1.5 (100 mW/cm^2), and on the determination of the activation energy, ΔE. The main parameters for each single layer are summarized in Table II.

Junction properties, carrier transport and photogeneration are investigated from dark and illuminated current-voltage (J-V) performed at different light intensity conditions and under an AM1.5 simulator (100 mW cm^{-2}).

3. Results and discussion

The low doping levels used (Table I) are responsible for the high ΔE values and for the low σ_d of the doped layers. As expected the presence of carbon leads to a decrease of the dark conductivity, an increase of the optical gap and to an increase of the activation energies and Urbach energies.

In Fig. 1 the JV characteristics in dark (a) and under AM1.5 illumination (b) are displayed.

TABLE II. Optoelectronic properties of the individual layers.

Cell 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

The JV characteristics of a pin device under illumination can be approximately described by using the transport equation of an ideal p-n junction [5], [6]]. The key cell characteristics such as: open-circuit voltage V_{oc}; short-circuit current J_{SC}, n factor and the reverse saturation current J_O were extracted, from the fit of the experimental data to the ideal J-V equation, and are listed in Table III.

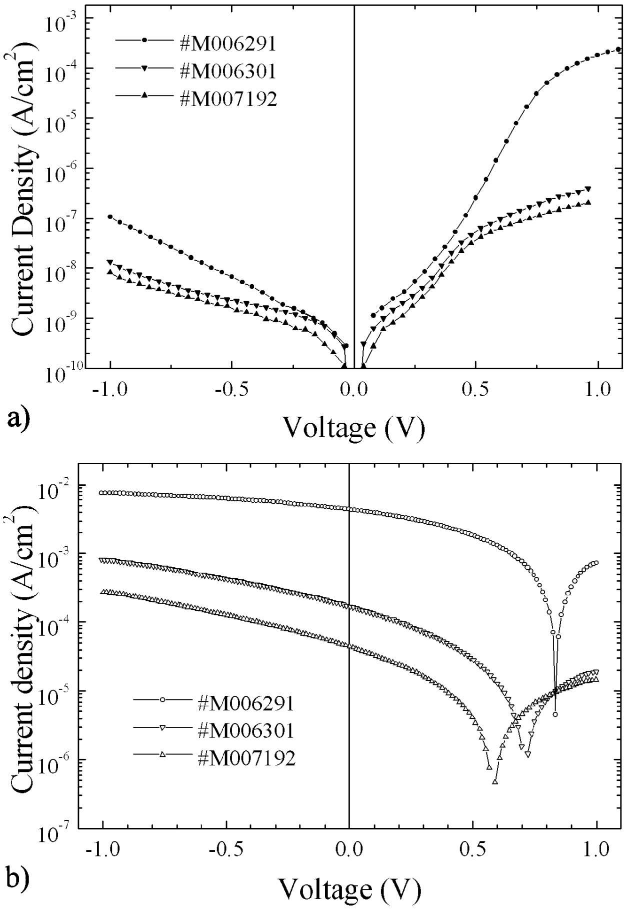

FIGURE 1. J-V characteristics in: (a) dark and (b) under AM1.5 illumination.

TABLE III. 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

Results show that in the heterojunctions structures the saturation current density and the value of the diode quality factor are high due to an increased recombination at the p and/or nSiC:H/Si:H interfaces. High series resistances around $10^6\Omega$ were also measured for the heterojunctions.

In dark, and under reverse bias the JV characteristics present a large current change and, in the voltage range analyzed, no saturation point is observed (Fig. 1a). Under AM1.5 the photocurrent is bias dependent (Fig. 1b) and the gain, defined as the ratio between the photocurrent under forward and reverse bias at the same voltage (+1V and -1V), is higher in the heterojunctions suggesting carrier injection from the doping layers to the i-layer. Under AM1.5 illumination, the high values of R_S are responsible, by the $J^2 \cdot R_S$ power losses resulting atypical JV characteristics and poor fill factors. It is interesting to notice that at low light intensity the sample # M006291 shows the normal JV characteristics (no bias dependent photocurrent collection), however as the light intensity increases the current starts decreasing around zero bias voltage and the fill factor decreases. We conclude that the atypical JV behavior can be explained with a series resistance circuit model.

In Fig. 2 the cell responsivity, R (A/W), as a function of the wavelength is displayed under no bias light condition (dark) for the three analyzed structures.

Results show that R depends on the cell configuration and decreases with the presence of wide band gap doped layers. Cell #M007192 presents an increased blue collection due to the higher front optical gap when compared with the other two cells.

In Fig. 3 we display, for each cell and at different optical bias intensities (ϕ_L), the spectral results normalized to the maximum value in dark, R_N. In the heterostructures (Fig. 3a and 3b) R_N decreases with ϕ_L. If a front highly resistive and wide band gap p-layer is used the spectral response is enlarged and the ratio between the illuminated and the dark spectral responses lowers. In the optical flux range analyzed the spectral response of the homojunction (Fig. 3c) remains light bias independent.

We used the AMPS device simulation tool to analyse the carrier transport under AM1.5 and zero voltage bias [7]. The typical band tail and gap state parameters of amorphous materials were taken as a basis, while the doping level was adjusted in order to obtain approximately the same layer conductivity as in the tested samples. Fig. 4 shows the simulated band diagrams for each configuration. In the heterojunctions the potential drop becomes dominant across the low conductive and wide gap doped layers (see Table II) and the electric field strength decreases significantly inside the i-layer, while in the homojunction the electric field remains high across all

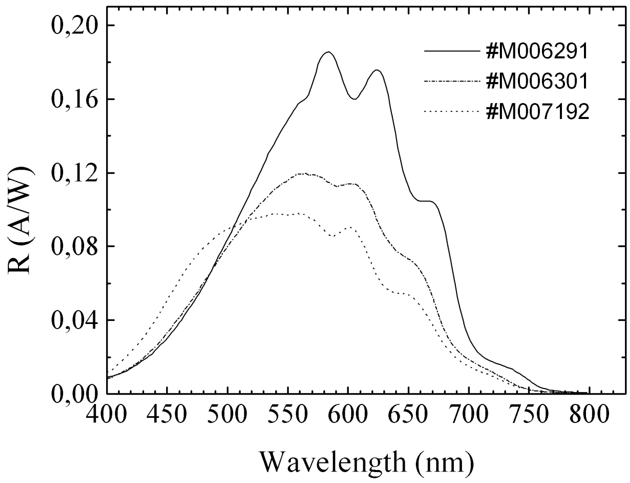

FIGURE 2. Responsivity as a function of wavelength under no bias light condition (dark) for the three analyzed structures.

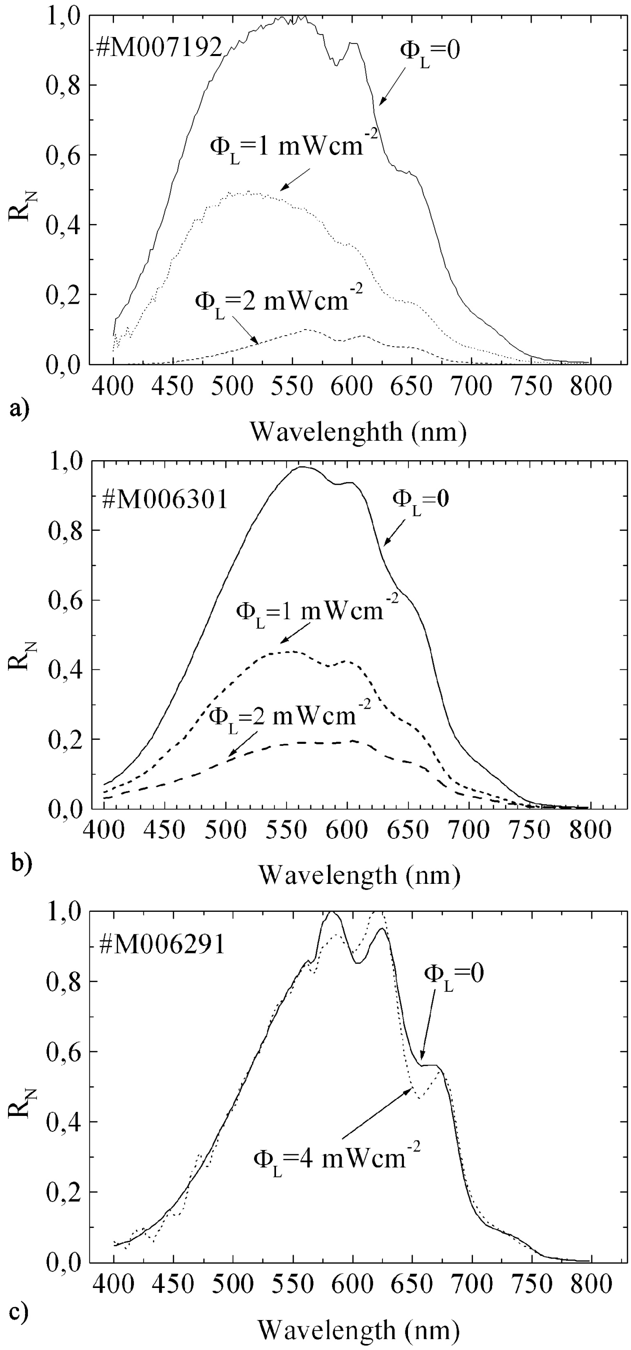

FIGURE 3. Normalized responsivities under different optical bias conditions for different configurations:
(a) p (SiC:H)/i (Si:H)/n (SiC:H);
(b) p (Si:H)/i (Si:H)/n (SiC:H) and
(c) p (Si:H)/i (Si:H)/n (Si:H).

the absorber layer. So, in the heterojunctions the photogenerated electrons and holes accumulate at the i-Si:H/pSiC:H and i-Si:H/nSiC:H interfaces, respectively, where they are trapped or recombine. The SiC:H doped layers act as blocking layers and prevent, under illumination, the electrons and holes to be injected into the i-layer. Here, the low field region is not enough to sweep the photocarriers to the contacts before they recombine resulting in a low collection. The field-

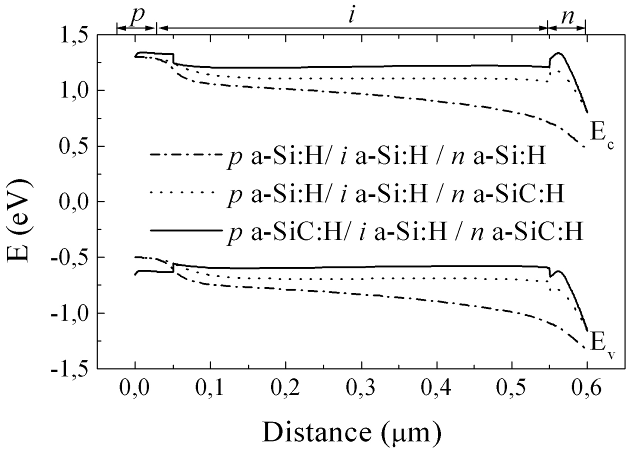

FIGURE 4. Energy band profile for the homo and heterojunctions (AM1.5; 0V).

dependent collection reduces the photocurrent at forward bias leading to atypical JV characteristics and poor fill factors.

4. Conclusions

Considerations about modified electrical field profiles and drift-diffusion transport mechanism were used to explain the atypical shapes of the light J-V characteristics and the enhanced ratio between the spectral responsivity in dark and under optical bias conditions in pin 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.

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