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Tuning the spectral distribution of p–i–n a-SiC:H devices for colour detection

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Abstract

ZnO:Al/p (SiC:H)/i (Si:H)/n (SiC:H) large area image and colour sensor are analysed. Carrier transport and collection efficiency are investigated from dark and illuminated current–voltage (*I*–*V*) dependence and spectral response measurements under different optical and electrical bias conditions. Results show that the carrier collection depends on the optical bias and on the applied voltage. By changing the electrical bias around the open circuit voltage it is possible to filter the absorption at a given wavelength and so to tune the spectral sensitivity of the device.

Transport and optical modelling give insight into the internal physical process and explain the bias control of the spectral response and the image and colour sensing properties of the devices.

Keywords: Spectral response; p–i–n Heterojunctions; Colour detection; Image sensor

1. Introduction

Amorphous silicon-carbon (a-SiC:H) is a material that exhibits excellent photosensitive properties. The possibility to modify its optical band gap enables the detection from the ultra-violet to the infrared part of the spectrum. This feature together with the strong dependence of the maximum spectral response on the applied bias has been intensively used for the development of colour devices. Various structures and sequences have been suggested [1,2]. In our group, efforts have been devoted towards the development of a new kind of colour sensor, the colour laser scanned photodiode sensors (CLSP) [3–5]. Here, simultaneous image and colour detection are achieved by combining the wavelength filtering property of silicon with the sensor responsivity dependence on the applied voltage. The optimisation of this trade-off demands a full understanding of the transport mechanism in p–i–n a-Si:H/a-SiC:H heterojunctions. The aim of this work is to describe the results of experiments as well as to discuss the usefulness of the a-SiC:H doped layers in the improvement of the sensor performance (image and colour sensing).

2. Experimental details and characterization

Large area amorphous single layers and p–i–n structures in the assembly glass/ZnO:Al/p (SiC:H)/i (Si:H)/n (SiC:H)/Al were produced by plasma enhanced chemical vapour deposition at 13.56 MHz radio frequency (PE-CVD) in a three chamber load-lock UHV-system [6]. Details of the deposition conditions and optoelectronic characterization of the single layers and devices are described elsewhere [7]. After the deposition of the amorphous layers, a back contact of aluminium was thermally evaporated which defines the active area of the sensor ($4 \times 4\ cm^2$). The thickness of the doped layers is approximately 50 nm and the intrinsic i-layer 500 nm. The deposition conditions of all the i-layers were kept constant while for the doped layers varying mixtures of silane and methane and low doping levels were used in order to produce highly resistive and wide bandgap layers. All the layers of

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Table 1
CH_4 flow (sccm) during the deposition process of the p–i–n a-SiC:H structures

	#M006291	#M006301	#M007192	#M011101	#M011102
p	–	–	20.00	40.00	20.00
i	–	–	–	–	–
n	–	20.00	20.00	20.00	–

The SiH_4 flow was kept constant in all the deposited structures.

sensor #M006291 are based on amorphous hydrogenated silicon, the n-layer of sensor #M006301, the p-layer of sensor #M011102 and the p- and n-layers of sensors #M007192 and #M001101 are based on a-SiC:H alloys. Table 1 reports the methane (CH_4) flow (sccm) used during the deposition of each layer of the sensor. The optical gap sequences for each p–i–n sensor are respectively: 1.8/1.8/1.8 eV; 1.8/1.8/2.1 eV; 2.3/1.8/1.8 eV; 2.1/1.8/2.1 eV and 2.1/1.8/2.3 eV.

The characterization of the device was performed through the analysis of the photocurrent and spectral response dependencies on the applied voltage, under different optical bias conditions (dark; and $\lambda_L = 450$, 550 and 650 nm; $0 < \Phi_L < 450\ \mu W/cm^2$). To suppress the dc components all the measurements were performed using the lock-in technique. The responsivity was obtained by normalizing the photocurrent, i_{ac}, to the incident flux under different light wavelengths, λ_S (in the range of 400–800 nm), and at different optical light bias, λ_L. The collection efficiency is determined by normalizing the photocurrent to the value at which the sensor responsivity becomes independent on the optical bias (around 1.5 V).

3. Results and discussion

3.1. Current–voltage characteristics

Fig. 1 shows current–voltage (*I–V*) characteristics in the dark (a) and under AM1.5 illumination of 100 mW/cm^2 (b).

As it was expected, the currents are different under positive and negative bias voltage. They depend on the doped layers composition, mainly under negative bias, and they decrease as the carbon content increases.

Results show that under reverse mode and in dark, the *I–V* dependence presents a large current change. No saturation points are detected and the currents cancel at different non-zero values of the applied voltage. Under AM1.5 illumination, the high values of serial resistances are responsible for power losses resulting in S-shaped *I–V* characteristics and poor fill factors.

The high density of defects located inside the SiC doped layers and at the interfaces act as charge reservoir leading to relaxation processes in the time window of the measurement (ms). The carrier response obtained in dark and under zero applied voltage depends on the sign of the trapped charges at the interfaces and it has to be taken into account in the diffusion-drift transport mechanism as will be analysed later.

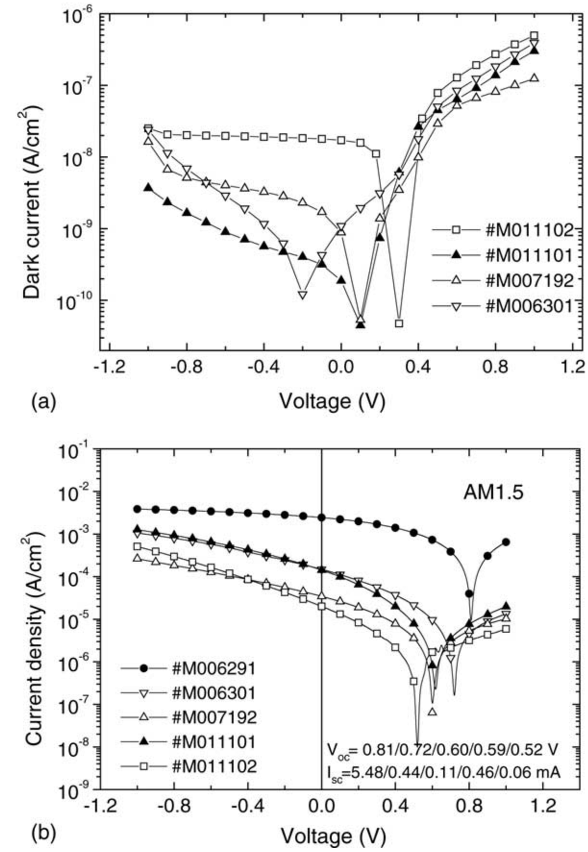

Fig. 1. Dark and illuminated current densities as a function of the electrical bias voltage.

3.2. The spectral sensitivity

Fig. 2 shows the sensors responsivity as a function of the applied voltage under different steady-state illumination conditions. Results show that for each sensor the responsivity depends strongly on both the optical and the electrical bias. As the applied voltage increases, the spectral sensitivity decreases continuously with a slope that depends on the optical bias and on the sensor structure.

In the dark (a), the spectral response becomes negative near the open circuit condition. Under green (b) or red (c) illumination, the spectral response behaviour is different. The decay is slower and even at bias higher than the open circuit voltage the response is positive, which reflects a diffusion-aided transport mechanism. The turn-off point and the slope of the spectral response depend on the carbon incorporation. As the carbon content increases, the spectral sensitivity always decreases. In the sensors having the n-layer based on a-SiC:H material the decay is slower and the red sensitivity enhanced.

3.3. Collection efficiency

For a set of sensors having different p-layers (see Table 1), in Fig. 3, the collection efficiency at 650 nm is displayed as

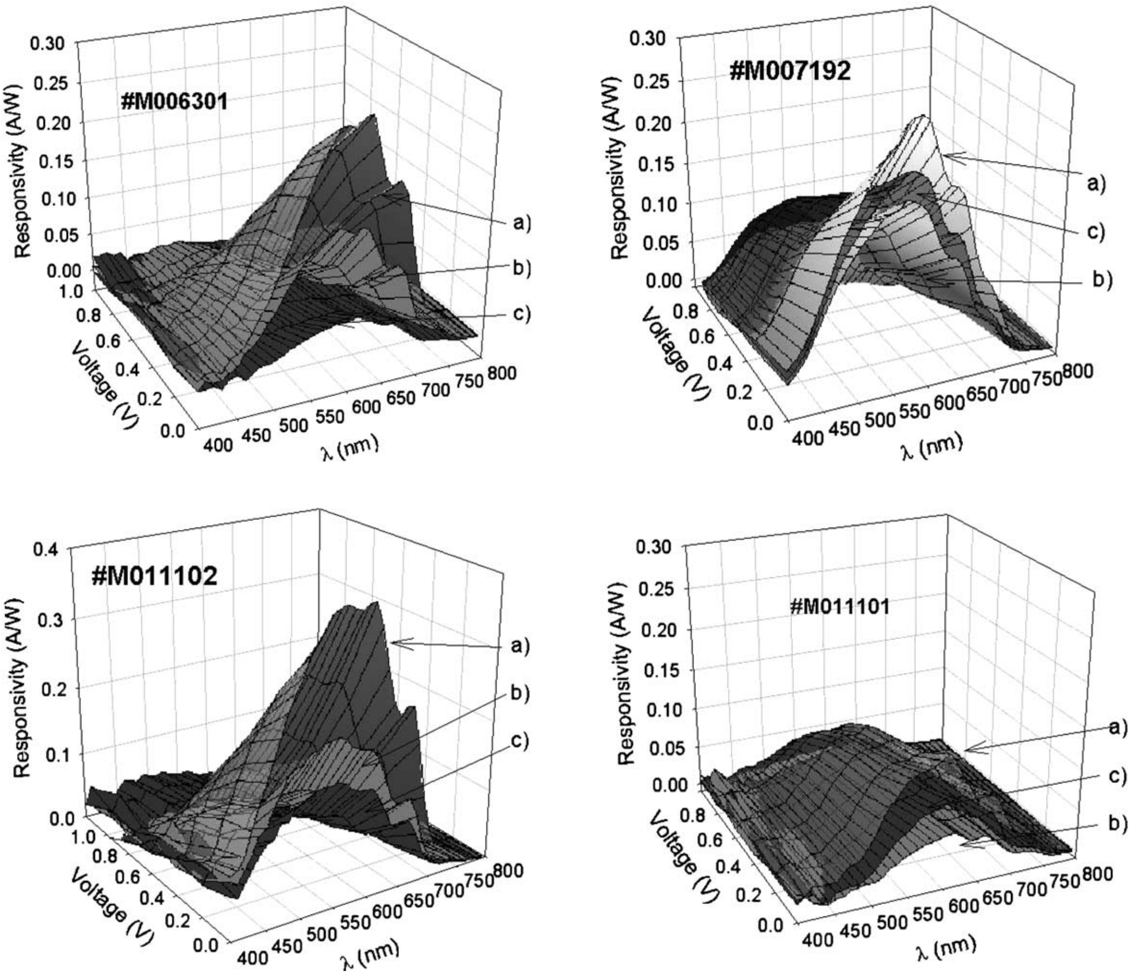

Fig. 2. Responsivity dependence on the applied voltage under steady-state light bias conditions: (a) in dark ($\Phi_L = 0$), (b) red (650 nm), and (c) green (550 nm), $\Phi_L = 10\ \mu W/cm^2$.

a function of the applied bias, in the dark and under two different optical bias illuminations.

As expected from Fig. 2, the collection efficiency at a given wavelength depends on the optical bias conditions (λ_L, Φ_L) and on the doped layer composition. As the applied voltage changes from negative to positive, the carrier collection decreases, in a steep way in the dark, and more slowly under illumination. This behavior allows for light-to-dark sensitivity and enables the device with image sensing properties [3].

For a drift-controlled device a change in sign near the open circuit voltage is expected. However, as the carbon content in the p-layer increases, the sign change shifts to higher values due to the increased flatness of the curves beyond this voltage. This effect is ascribed to a reinforcement of the internal electric field due to the trapped charges at the front or both interfaces.

For the sensor #M006301, in Fig. 4 we present the i_{ac} signal at 650 nm ($\Phi_S = 41.8\ \mu W/cm^2$) as a function of the applied voltage, under different steady-state bias illuminations ($\lambda_L = 450$, 550 and 650 nm) and light intensities ($0 < \Phi_L < 450\ \mu W/cm^2$).

Results show that the ac signal decreases as the light intensity increases, and it is suppressed at forward bias voltages whose values are dependent on λ_L but almost independent on Φ_L in the low flux range. The colour suppression ($i_{ac} = 0$) is achieved at lower voltages under blue (0.25 V) than under green (0.4 V) or red (1 V) illumination. These experimental results show that the carrier collection strongly depends on the penetration depth of the bias light, it is independent on the intensity and can be suppressed by tuning the applied voltage to the value that leads to the collapse of the electric field at the interfaces.

Colour extraction is only possible if the cross points between both light and dark curves are sufficiently separated (#M006301, #M007192). This is the case displayed in Fig. 5a where the image intensity (defined as $i_{ac}(\Phi_L = 0) - i_{ac}(\Phi_L)$ [8]) is plotted as a function of the electrical bias voltage. Fig. 5b shows the acquired image from a two strip red and green colour picture projected on the sensor #M007192 (($\Phi_L = 10\ \mu W/cm^2$).

Results show that at −0.7 V bias, the image intensity for the red or the green image presents the same magnitude and

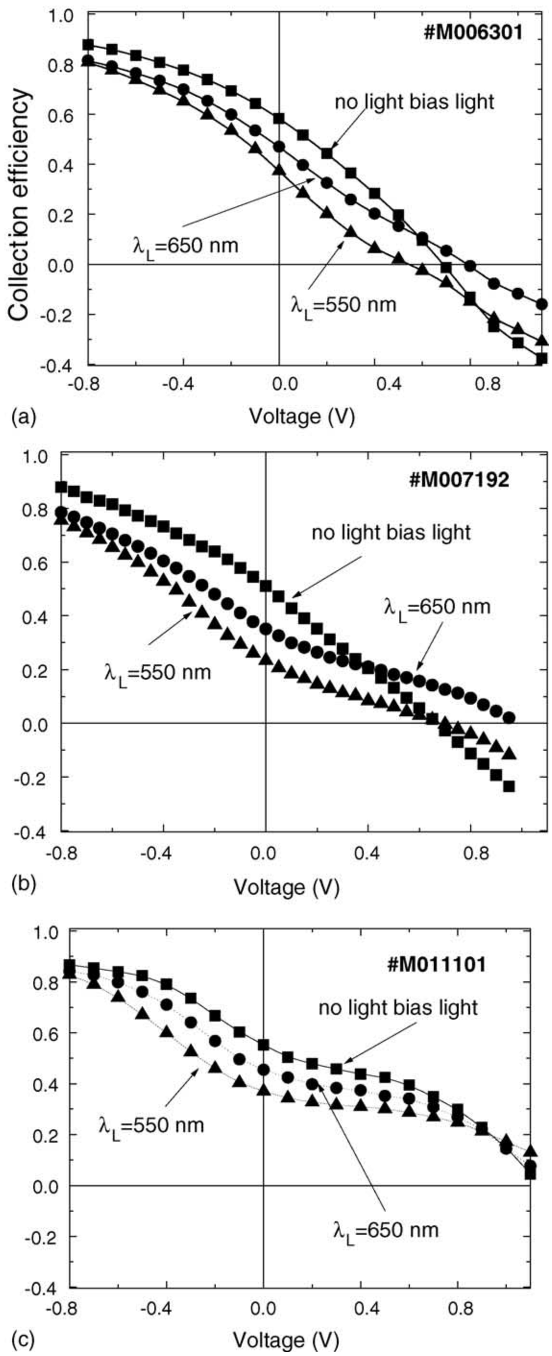

Fig. 3. Collection efficiencies at 650 nm ($\Phi_S = 1\ \mu W/cm^2$) as a function of the applied voltage in the dark ($\Phi_L = 0$) and under red and green illumination ($\lambda_L = 550$ and 650 nm; $\Phi_L = 10\ \mu W/cm^2$).

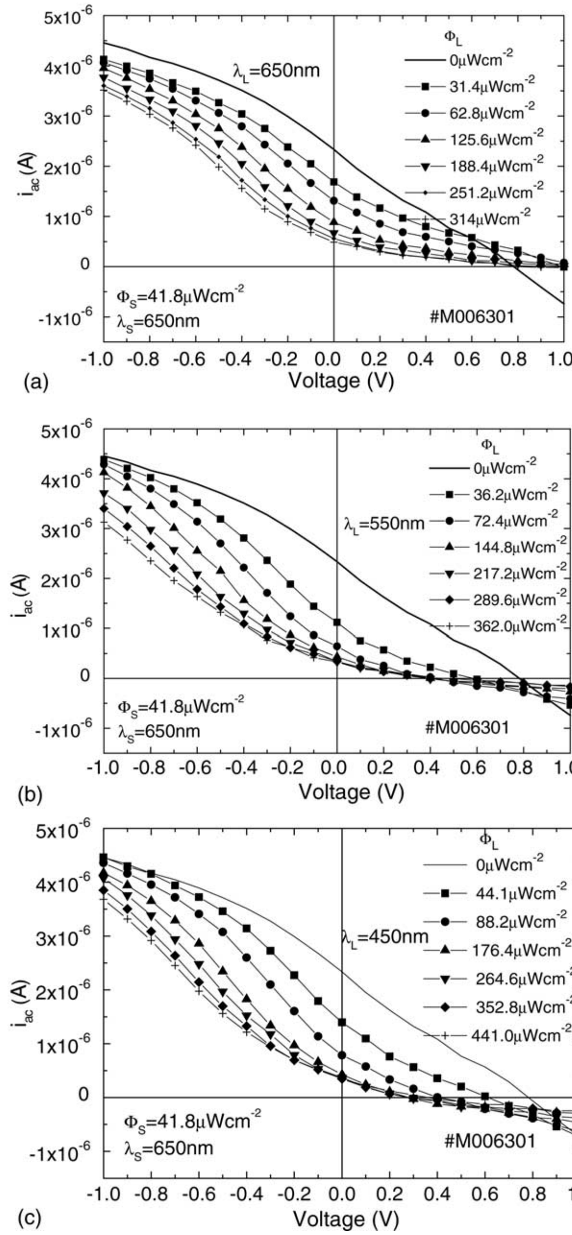

Fig. 4. i_{ac} Signal at 650 nm ($\Phi_S = 41.8\ \mu W/cm^2$) as a function of the applied voltage under different bias illumination intensities (dark, $\Phi_L = 0$; λ_L: (a) 450 nm; (b) 550 nm, (c) 650 nm; and $0 < \Phi_L < 450\ \mu W/cm^2$).

polarity (Fig. 5a). No colour information can be extracted, which leads to a black and white image. In this mode the brightness of the image (see Fig. 4) is proportional to the output signal (i_{ac}), which gives to the sensor the ability of acquiring monochrome grey level images. Colour information can only be obtained under forward bias (Figs. 4 and 5). In sensor #M007192 by tuning the voltage to +0.4 V the red signal is suppressed allowing green recognition. The red information is obtained at +0.7 V where the green signal goes down to zero. So, by combining the signal information at these voltages (+0.4, +0.7 and −0.7 V) enables the reconstruction of the colour picture without the need of colour filters or stacked structures [2].

3.4. Numerical simulation

To understand the bias controlled spectral response we took into account the experimental data (#M007192) and the results obtained through a numerical simulation based on the ASCA simulator [9]. Fig. 6 shows the simulated potential (a) and electrical field (b) profiles as a function of the applied

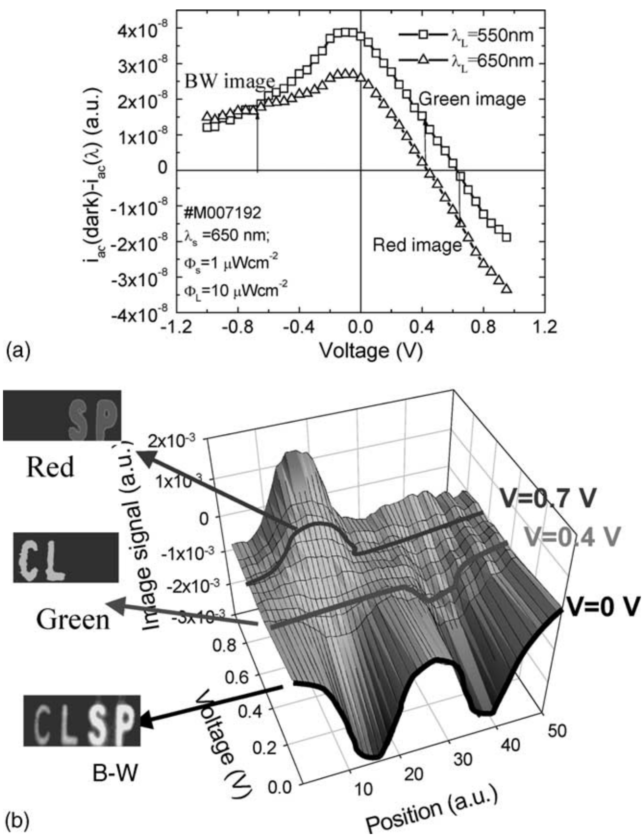

Fig. 5. Image intensity acquired using the CLSP colour sensor #M007192 as a function of the electrical bias voltage: (a) uniform illumination; (b) under a two strip colour picture. The inserts are images acquired with the sensor at the same voltages.

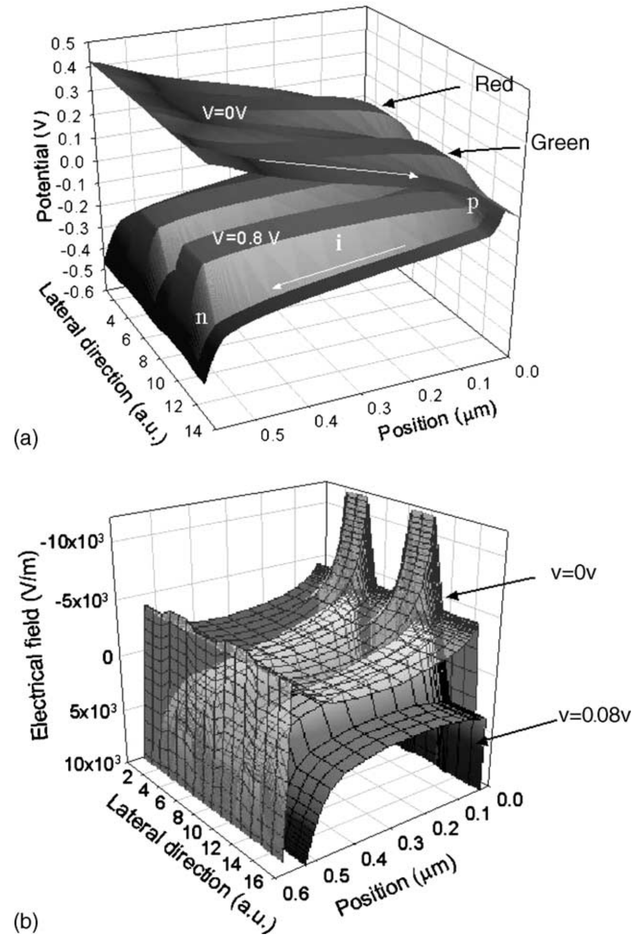

Fig. 6. Simulated potential and electric field profiles under different illumination conditions and applied voltages. The arrows are used only to guide the eyes in the current flow across the device.

voltage for the same colour picture (two red and green strips, ($\Phi_L = 10\ \mu W/cm^2$).

Simulated results reveal that the potential and electrical field profiles are very sensitive to the bias illumination confirming the image sensing properties of the devices. In the dark regions, the bias voltage controls the current flux across the *i*-layer while at the illuminated ones the potential drop occurs mainly over the slightly doped layers, due to their high resistivity. Here, the potential across the *i*-layer is reduced and even flattens which ensures the presence of a large neutral region inside the absorber.

Driven by the junction internal electrical field, in the low voltage regime, the carriers generated by the probe beam (λ_S, Φ_S) inside the dark regions are collected. Under illumination, as the light intensity increases, the potential across the bulk flattens leading to a decrease on the photocurrent signal proportional to the image brightness. This effect is the basis of the monochrome image recognition [3].

Colour sensitivity depends mainly on the penetration depth of the light and on its influence at the induced depletion region at the p and n layers. Under red illumination and at high forward bias the electric field is always zero in the bulk, and enhanced mainly at the i–n interface that becomes fully depleted. An inversion layer opposite to the applied voltage is induced and a small increase in the applied bias voltage produces an increase of the electron density at the i–n interface that leads to a transition from the primary to the secondary photocurrent regime at higher applied voltages (Fig. 6b). Under blue/green illumination the light is absorbed mainly near the p–i interface changing the carrier accumulation in an opposite way.

4. Conclusions

Heterostructures based on p–i–n a-SiC:H were analysed under different light and voltage bias conditions. Considerations about band misalignment, modified electric field profiles and drift-diffusion transport mechanism were used to explain the atypical shapes of the light *I–V* characteristics, the enhanced ratio between the spectral responsivity in the dark and under optical bias conditions, and fine tune of the spectral sensitivity under forward bias. Numerical simulation gives insight into the physical process and explains the fine tuning of the wavelength with the applied voltage in those devices.

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Biographies

Manuela Vieira was born in Lisbon, Portugal. In 1986, she received the Masters of Science in solid state physics-microelectronic and in 1993 the PhD in semiconductor materials both from the New University of Lisbon. She is full professor in electronics inside the Department of Electronics Telecommunication and Computers (ISEL, Portugal) and the head of the Group in Applied Research in Microelectronic Optoelectronic and Sensors-GIAMOS. She has several scientific papers and 20 years of experience in the field of thin films and devices, her research activities have been mainly related to the development of optical sensors.

Paula Louro was born in Portugal in 1967. In 1990 she became researcher in EID Lisbon, Portugal, in the Department of Optoelectronics. She graduated in physics by the faculty of sciences from the University of Lisbon in 1990. In 1995, she received the Masters of Science in material engineering by the 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 and devices.

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