Design, characterization and modeling of a tunneling break-down photodiode integrated in a standard 0.5μm CMOS technology

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Summary

A low-voltage tunneling-breakdown photodiode has been designed, fabricated and characterized. Tests have been done to find dark-current, break-down voltage, turn on voltage, series and shunt resistance as well as spectral response. An average break-down voltage of 1.1V states the device suitable for low-voltage circuits. After characterization, a model aimed for simulation in Spice was developed.

Keywords: Photodetectors, Photodiodes, Solid state detectors.

1. Introduction

Silicon photodiodes are widely used in image sensing and acquisition for their acceptable linearity, low noise and wide spectral response. While high performance devices such as PIN or avalanche photodiodes usually require large sensitive area [1], silicon photodiodes integrated in standard CMOS technology could be designed under area/sensitivity constraints, since the image processing circuitry is usually integrated in the same substrate as the focal plane, in order to exploit the very large integration capability of CMOS circuits.

The constant scaling process experienced by CMOS technology, leads to the fabrication of microcircuits in heavily doped substrates as well as the use of reduced power supply. Under these circumstances, an image sensing element, such as a photodiode, designed with reduced area and highly doped PN regions, trends to present a low breakdown voltage mainly governed by tunneling mechanism [2]. In this scenario, a trade-off between sensitive area and breakdown voltage could be an appropriate criterion for the design of a photodiode aimed to be used in active-pixel circuits. As it is well known, in order to design the circuitry associated with an active-pixel imager, circuit simulation is an essential step, here, it is highly desirable to include all the elements acting in the system under design, in this sense, to have an accurate model of the sensing element included in the circuit under design, is demanded [3].

This work presents the design, characterization and modeling of a silicon photodiode integrated in a standard 0.5µm CMOS technology. Measurement results show the proposed sensor as a good candidate to be used in an image sensing matrix formed by active-pixel elements energized by 1.5V, which is currently under design. Section 2 provides a description of the proposed device. Section 3 presents the parameter description and measurement setup. The development of a model aimed for the static circuit simulation of the present photodiode in Spice based in measurement data are presented in Section 4. This section shows the simulation results using the proposed model comparing it with the data measured experimentally. The discussion of the final model is presented in Section 5. Some conclusions and future works are given in Section 6.

2. Proposed photodiode structure

Standard CMOS technology offers different choices to design a photodiode. Fig. 1 presents the layers included in the available technology.

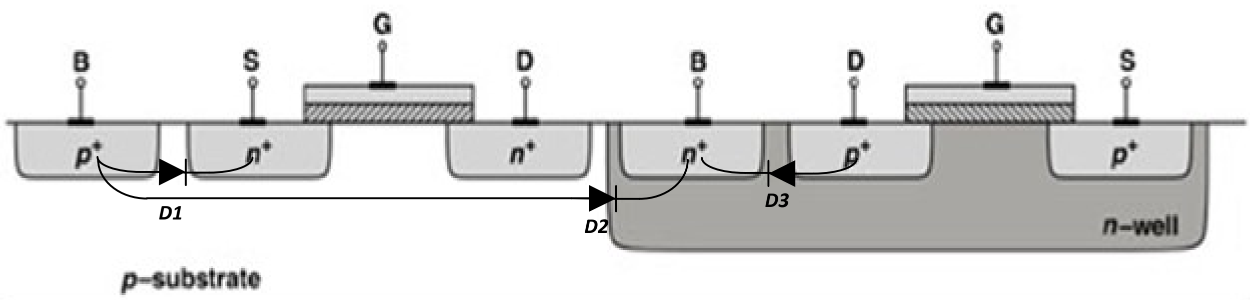


Fig. 1. N-well CMOS technology.

The diodes marked in Fig. 1 as *D1* to *D3* represent the different possibilities to design and fabricate a photodiode in a standard n-well CMOS technology. *D1* represents a diode fabricated using the initial p-substrate of the whole chip and the n+ diffusion used to create the source/drain region of an n-channel MOS transistor. *D2* presents a diode designed using the n-well region for the cathode and again p-substrate for the anode. Since in normal operation of a CMOS chip, the p-substrate is connected to ground or to the most negative power supply, this hard connection could lead to circuit design restrictions. Finally, *D3* shows a diode formed by the p+ source/drain region of a p-channel MOS transistor. As it can be seen, this structure has the advantage of having both the anode and cathode of the photodiode free for connection to any point in the circuit where it is being used. Besides, the last diode has, according to the literature [4], a spectral response centered on 600 nm, which states this kind of photodiodes more suited for image sensing in the visible range. The first two structures have their spectral response centered at 700nm, which leaves them more adequate for sensing in the near infrared [4]. Figure 2 shows a micro-photograph of the fabricated element.

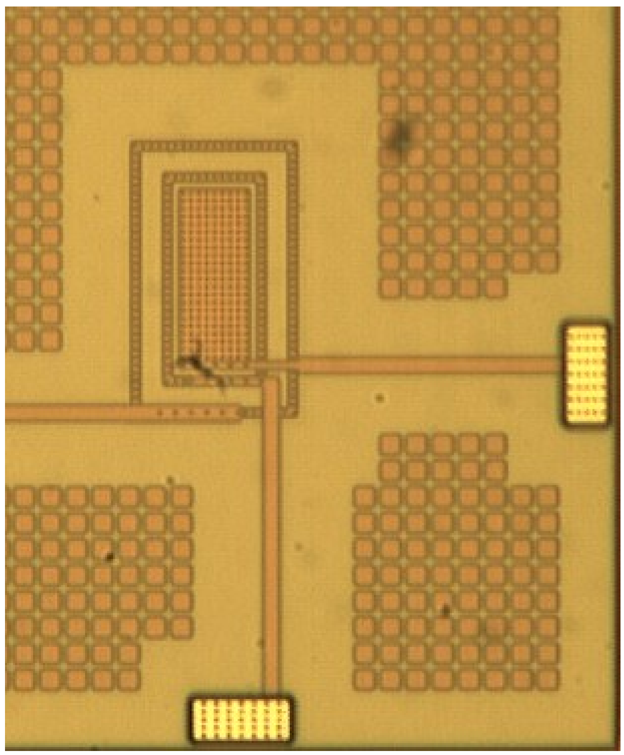


Fig. 2. Device Microphotograph.

The proposed device has a rectangular shape of 21.6μm by 42.6μm. As described before, the available technology is a three-metal double-polysilicon CMOS technology with 0.5μm of minimum length. It has a P-doped substrate and an N-well is provided for designing P-channel MOS transistors. In this way, anode is done by a P+ diffusion over an N-well region forming the cathode. The device is surrounded by a guard ring which is connected to the substrate. Anode and cathode terminals are connected to the package of the integrated circuit. The circuit die is encapsulated in a DIP 40 ceramic package with an open cavity. Fabrication and wire bonding were accomplished through the Mosis Service [5].

3. Parameter description and measurement setup

Static characterization of a photodiode requires several measurements. Figure 3 shows the main static parameters of a photodiode.

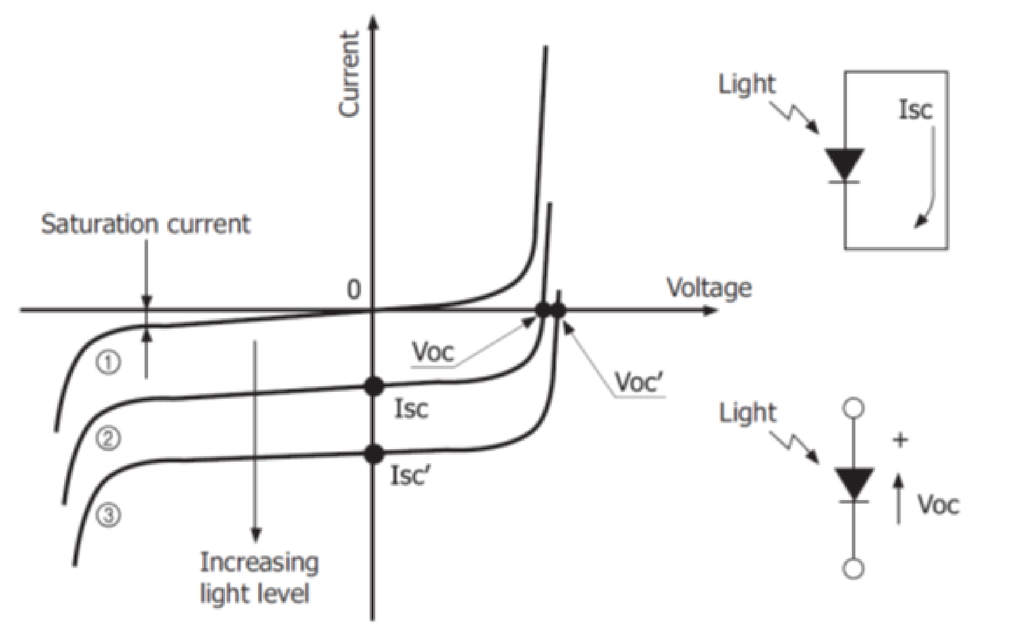


Fig. 3. Static Parameters of a Photodiode.

A silicon photodiode, as the one reported here, behaves as a silicon rectifier diode without incident light. When light falls on the photodiode, the typical characteristic of the diode moves down wards from its dark position in 1 to 2 in Fig. 3. If the power of the incident light increases, the curve goes even more down wards to position 3.

From Fig. 3 it can be seen how a photodiode produces a photocurrent even without applied voltage to its terminals. Since a zero voltage is referred as a short circuit, then this current is called "short circuit current" and is represented as "*Isc*".

On the other hand, a voltage is sustained without needing a current across the diode. Since a zero current is referred as an open circuit, this voltage is called "open circuit voltage" and is represented by "*Voc*".

As in every diode, in order to model properly its behavior, it is also needed to find: on voltage (*Vj*), reverse breakdown voltage (*Bv*) and series resistance (*Rs*). These last parameters are extracted from the dark characteristic and are shown in Fig. 4.

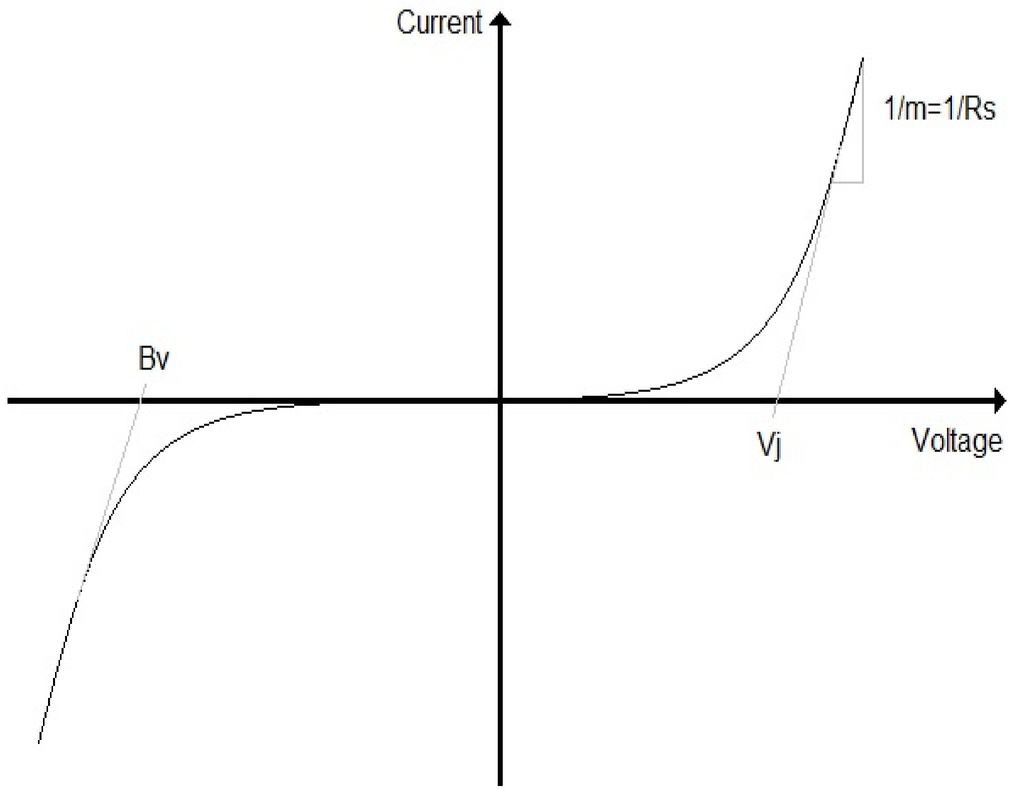


Fig. 4. Definition of *Vj*, *Bv* and *Rs* in a Diode.

To perform measurements, a basic automated data acquisition system was implemented. It comprises an electrometer (Keithley 6517A) controlled by a computer via GPIB interface (NI GPIB-USB-HS), the device under test (D.U.T.) was put in a

Faraday's cage to diminish the noise. All tests were done in ten samples. The average values are reported here. Figure 5 shows a schematic of this test setup.

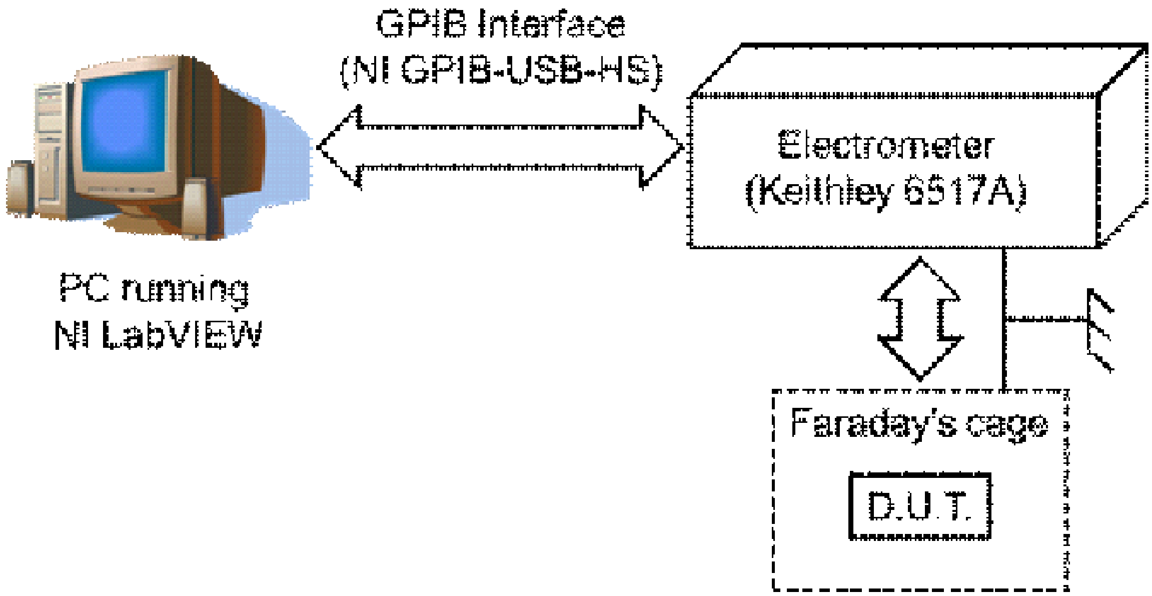
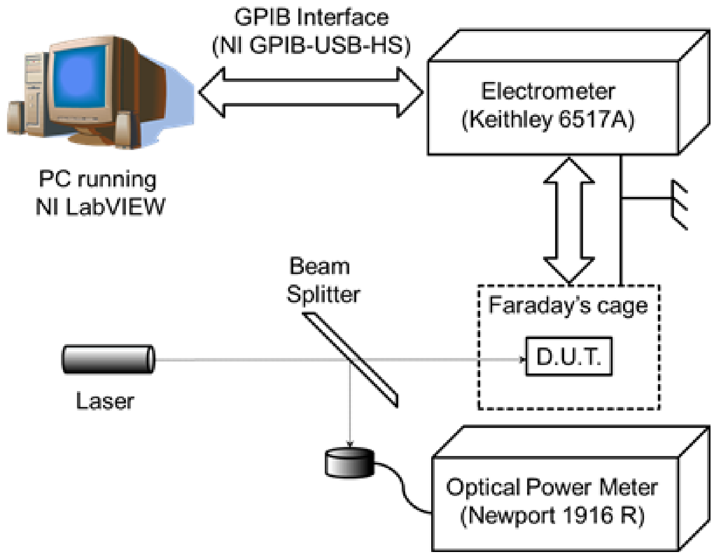
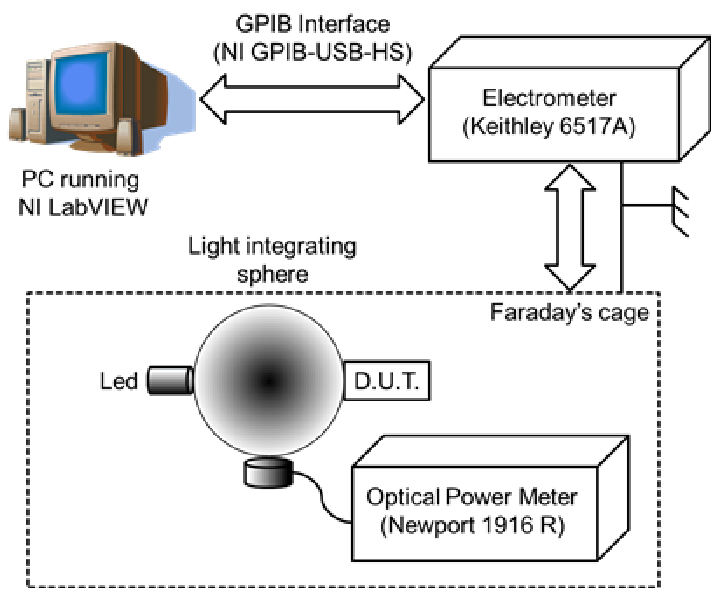


Fig. 5. Test Setup Used to obtain Dark Characteristics.

After some modifications, the same basic test setup of Fig. 5 was used to perform the characterization of the spectral response of the device under test. For this purpose, seven low-power semiconductor lasers (850, 830, 817, 780, 635, 532, 402 nm) and six LEDs (610, 590, 518, 460, 450, 405 nm), characterized with a spectrometer based in Newport MS257 monochromator, were used as light sources to excite the sensors. Light coming from LEDs was concentrated by an integrating sphere to reduce losses of energy. The irradiance of all lighting elements was measured with an optical powermeter (Newport 1916 R). The resulting current captured by the electrometer was divided by the irradiance to obtain the spectral responsivity of the photodiode. Spectral response measurements of photodetectors are usually done by means of a white light source passed through a monochromator [6]. The lack of this instrument leaded to use in this



(A)



(B)

Fig. 6. Test Setup used to obtain the Spectral Response using (A) Lasers and (B) Leds.

experiment the low cost characterization method described here. Figure 6 shows the modifications done to the basic setup in order to measure the spectral response.

4. Measurement Results and Modeling

Measurement of the dark characteristics was first performed. Figure 7 shows measurement results of ten samples, from this I-V curve, the static parameters described in Fig. 4 were obtained [7]. Linear regression was applied to the straight line portions of the curves (Fig. 4) and fitted with a first order polynomial of the form:

$$y = mx + b \tag{1}$$

From Eq. 1, *Rs*=1/m. Equating the expression to zero and solving for x, *Vj* or *Bv* can be obtained.

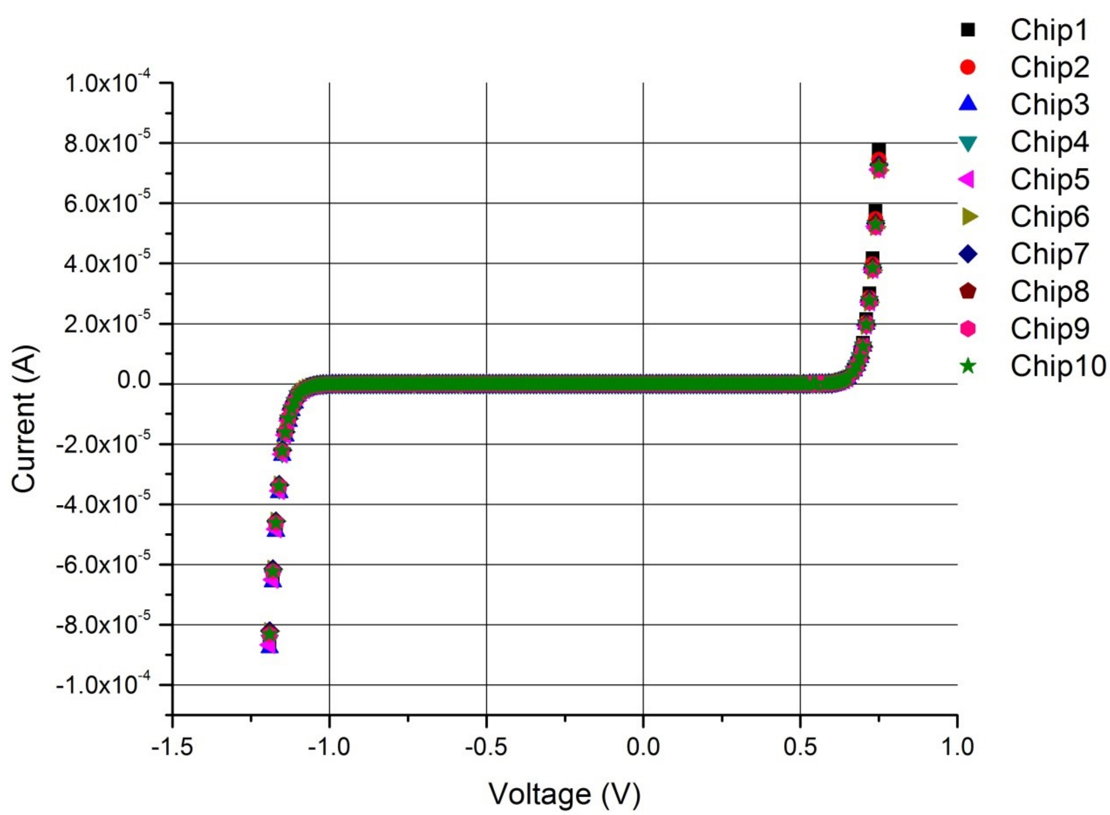


Fig. 7. Measurement results of the Dark Characteristics.

After applying linear regression analysis the averaged parameters obtained are summarized in Table 1.

Parameter	Symbol	Value
Saturation Current	*Is*	-1.43336E-008A
Series Resistance	*Rs*	1.2241e+003Ω
On voltage	*Vj*	0.6768V
Breakdown voltage	*Bv*	-1.15V
Current at on voltage	*Ikf*	1.27E-006A
Current at breakdown voltage	*Ibv*	-22.3E-006A

Table 1. Static Parameters of the Diode (Dark).

A reverse breakdown voltage around 1V was observed. This is typical for diodes with highly doped P/N regions. The small dimensions of the diode under analysis also contribute to the tunneling breakdown of these diodes since it increases the internal electric field in the union.

Parameters presented in Table 1, allow developing a model suited for circuit simulation in Spice. As it is well known, Spice models the current of a diode in forward bias according to the expression:

$$I_D = I_S\left(e^{V_D/nV_T} - 1\right) \qquad (2)$$

Where, I_D is the diode current, I_S the saturation current, V_D the voltage across the diode, V_T the thermal voltage (approximately 26mV at 300ºK) and n a dimensionless correction factor.

Curve fitting in Matlab was used to find an optimal value for n. After several iterations, a value of 1.68 was obtained. With this n factor and the parameters in Table 1, the following Spice model was written:

```
.MODEL PHOTODIODE D(IS=1.43336E-008 BV=1.15 RS=1.2241E3 NBV=1
VJ=0.6768 IBV=22.3E-006 IKF=1.27E-006 N=1.68)
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Figure 8 shows simulation results using the model defined above.

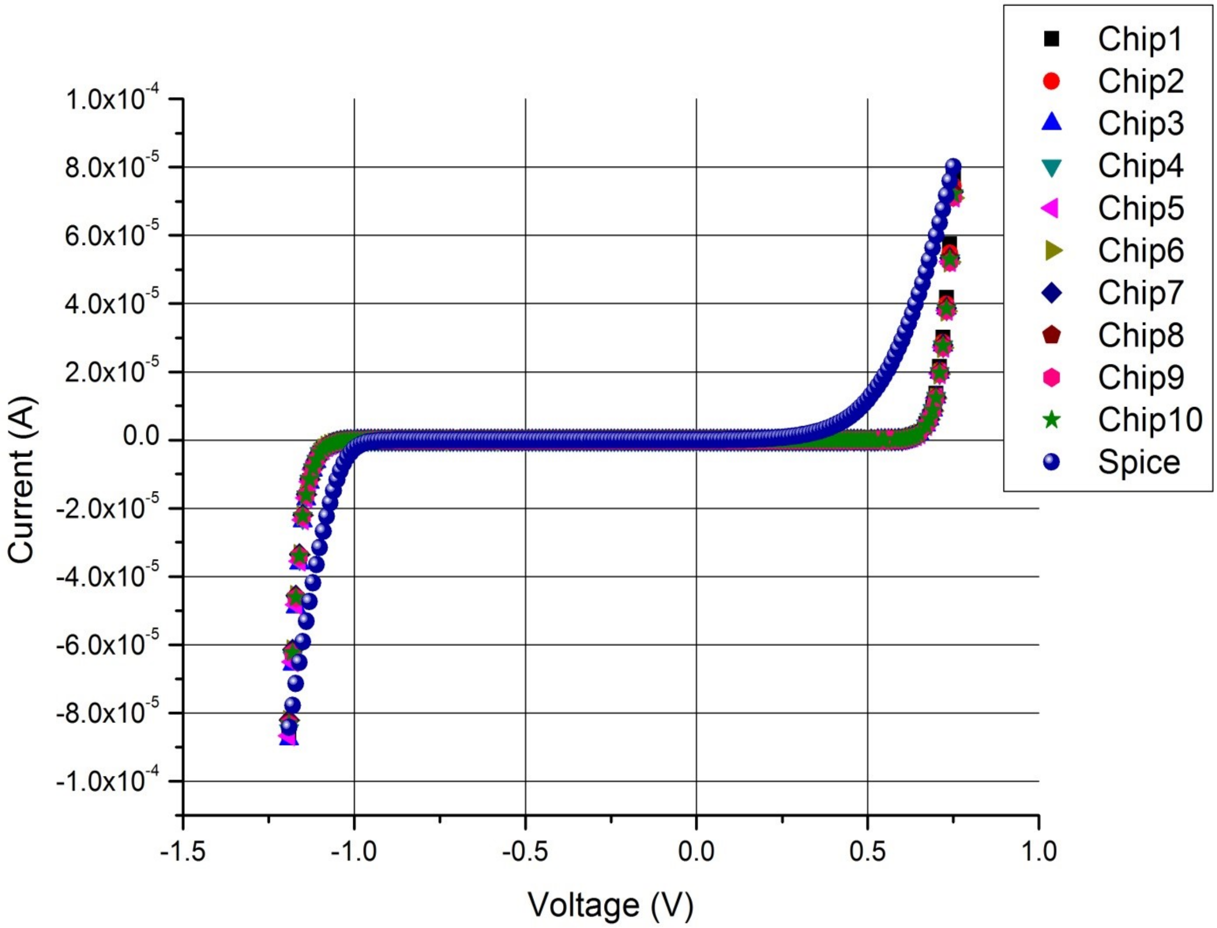

Fig. 8. Simulation results using simple Spice model.

As it can be seen, some error exists specially noticed in the breakdown and turn-on regions. This is due to the assumption done by Spice, which assumes diode operation in high injection regime in the forward region. The levels of current in the experiments move the device to the low injection regime of operation, where the simple correction factor n leads to a poor model [8].

To overcome this discrepancy, an exponential function of three terms was used. The general form of this function is:

$$I_D = I_{S0} + I_{S1}\left(e^{V_D/V_{T1}}\right) + I_{S2}\left(e^{V_D/V_{T2}}\right) + I_{S3}\left(e^{V_D/V_{T3}}\right) \qquad (3)$$

Two of these functions, namely an exponential decay and increase, were used to model the left and right portions of the curve in Fig. 8. The values found for the factors in Eq. 3 are given in Table 2.

In order to implement these functions in Spice, arbitrary behavioral current sources were used. For circuit simulation, due to its great performance and its acquisition free of charge, the LTSpice program was chosen [9]. In LTSpice, and arbitrary behavioral current source is called with the "`b`" circuit element.

Factor	Value for decay	Value for increase
Is_0	2.09151E-8	3.46296E-8
Is_1	-8.98617E-22	6.01422E-9
Is_2	-8.66978E-22	6.01423E-9
Is_3	-6.61537E-22	6.01424E-9
V_{T1}	-0.0312	0.0894
V_{T2}	-0.03121	0.0895
V_{T3}	-0.03125	0.0896

Table 2. Estimated Factors for Eq. 3.

Figure 9 shows simulation results using the proposed model. Although some discrepancy keep on being observed in the forward turn on region, it is less when compared with the Spice simple model, moreover, it is not of significant importance, since a photodiode is normally used with zero or negative applied potential. In the negative breakdown region, very good accuracy is observed. It is important to have a good model for this region because reaching the breakdown voltage causes severe deterioration of the device performance.

The photocurrent response of the device is depicted in Fig. 10. The typical I-V characteristic of a photodiode is observed. Figure 10 displays the curves obtained with the lasers of 850nm, 830nm, 780nm, 635nm, 532nm and 402nm. The sensor has a peak response at a wavelength of 532 nm (green-light laser). Since this is a P+-N-well junction, this behavior is consistent with previous reported results [10]. A curve of the normalized spectral responsivity of this photodiode, using all the previous mentioned

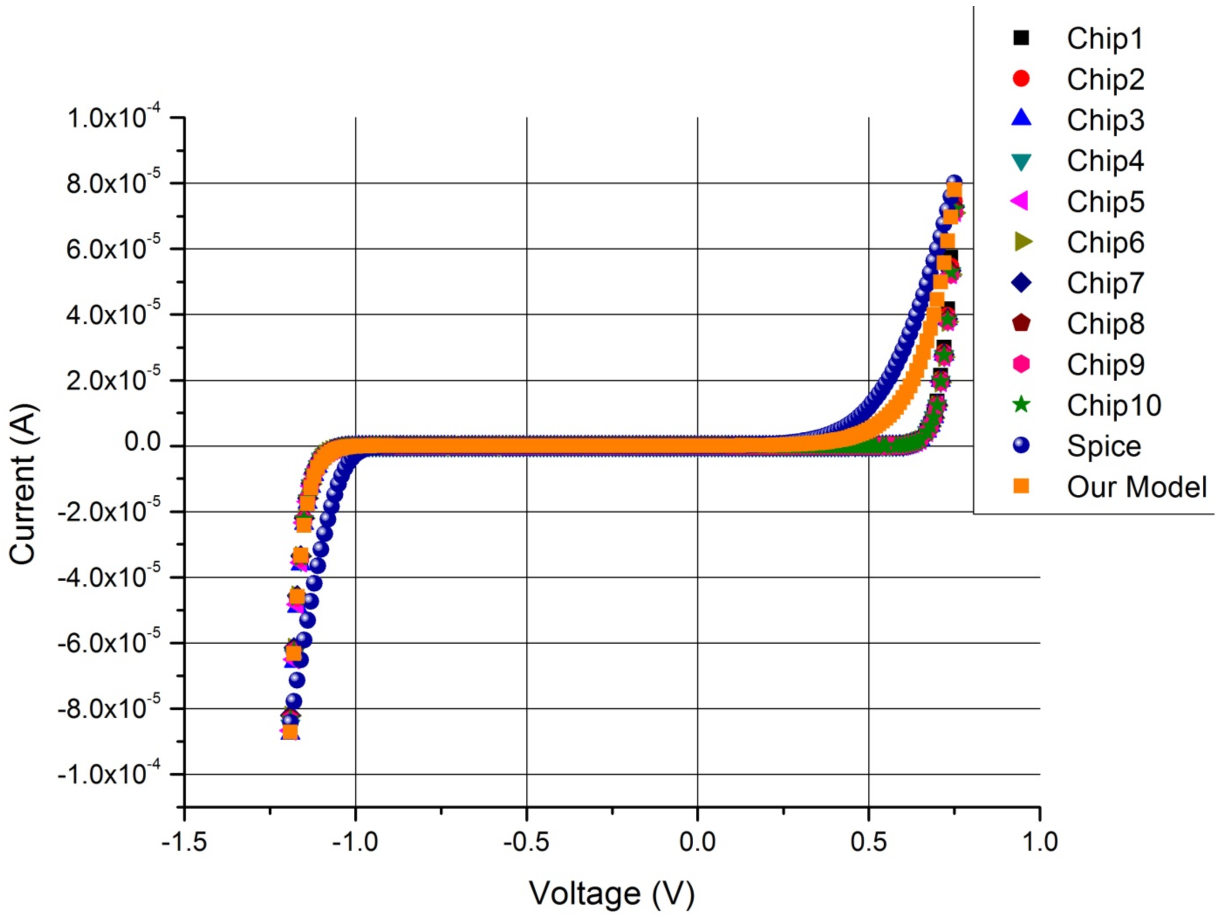

Fig. 9. Simulation results using the proposed model in Spice.

light sources, is given in Fig. 11. As it is well known, responsivity was obtained for each light source according to the expression:

$$\Re = \frac{I_{Ph}}{P_{In}} \tag{4}$$

Where, $\Re$ is the responsivity, I_{Ph} the photocurrent and P_{In} the optical power incident on the device. It has units of A/W. It is a usual practice to divide the responsivity obtained for each wavelength by its peak value and to express this metric in terms of relative or normalized responsivity.

As it can be noticed in Fig. 10, for voltages in the device between breakdown and turn on, it behaves as a current source, for this reason, the typical model of a photo diode includes a current source to represent photocurrent, as shown in Fig. 12A.

In the proposed model, the diode has been replaced by the previous mentioned behavioral sources. In order to model the photocurrent, an additional behavioral current source (BL) is parallel connected to the previous. The function of this third source is to

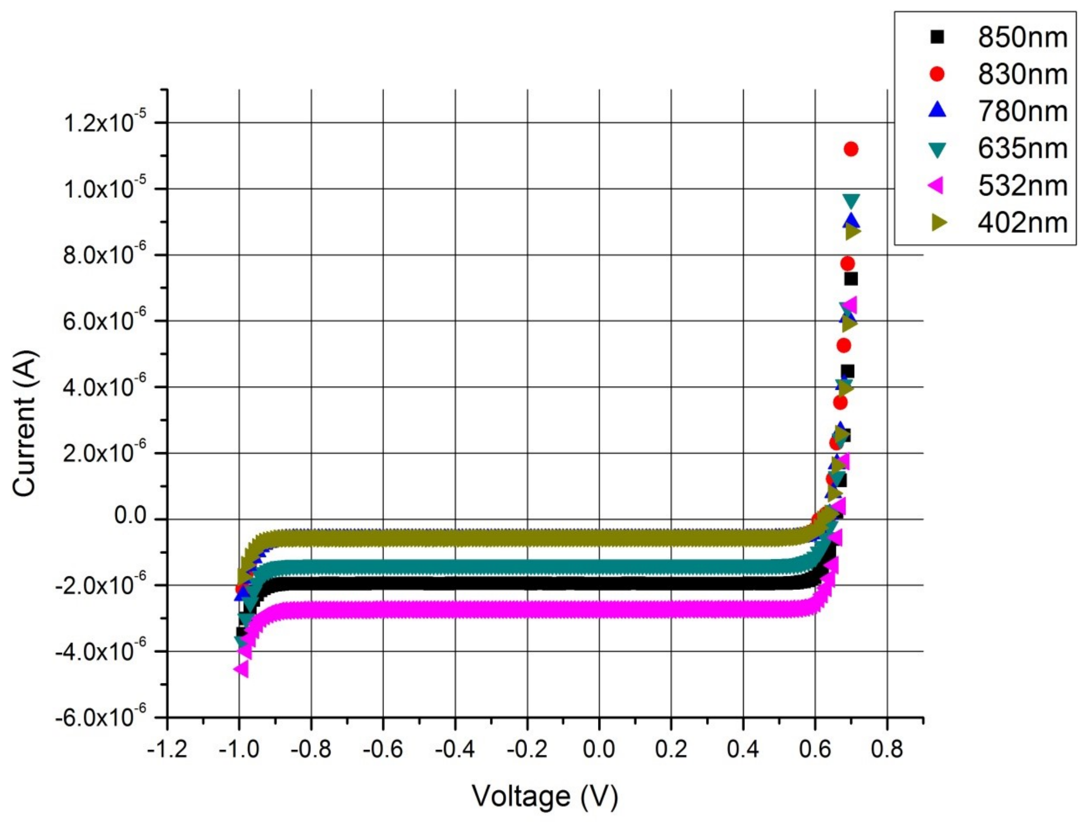

Fig. 10. Measured Photocurrent response for six lasers of different wavelength.

introduce the fraction of the optical power converted in current. For this purpose, a voltage source (V_S) with a load resistance (R_l) of one ohm is included as control element for the current source. Doing this, by Ohm's Law, voltage and current across the load are equal and its dissipated power is:

$$P_{Dis} = V_S^2 \tag{5}$$

Then the control factor (k) of this current source is:

$$k = \Re \times V_S^2 \tag{6}$$

The user of the proposed approach has to give a voltage equal to the square root of the incident power in V_S and the $\Re$ reported in Fig. 11, corresponding to the incident light. The schematic of Fig. 12 (B) represents the proposed model including *Rsh*, *Rs* and *Cj*

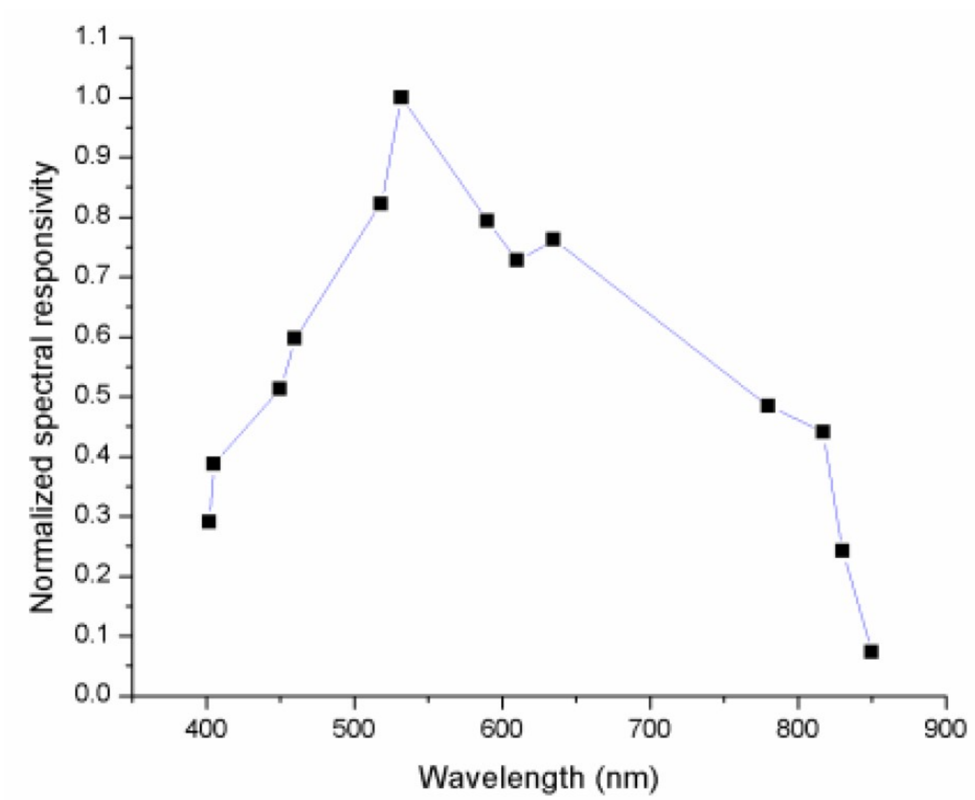

Fig. 11. Spectral Responsivity.

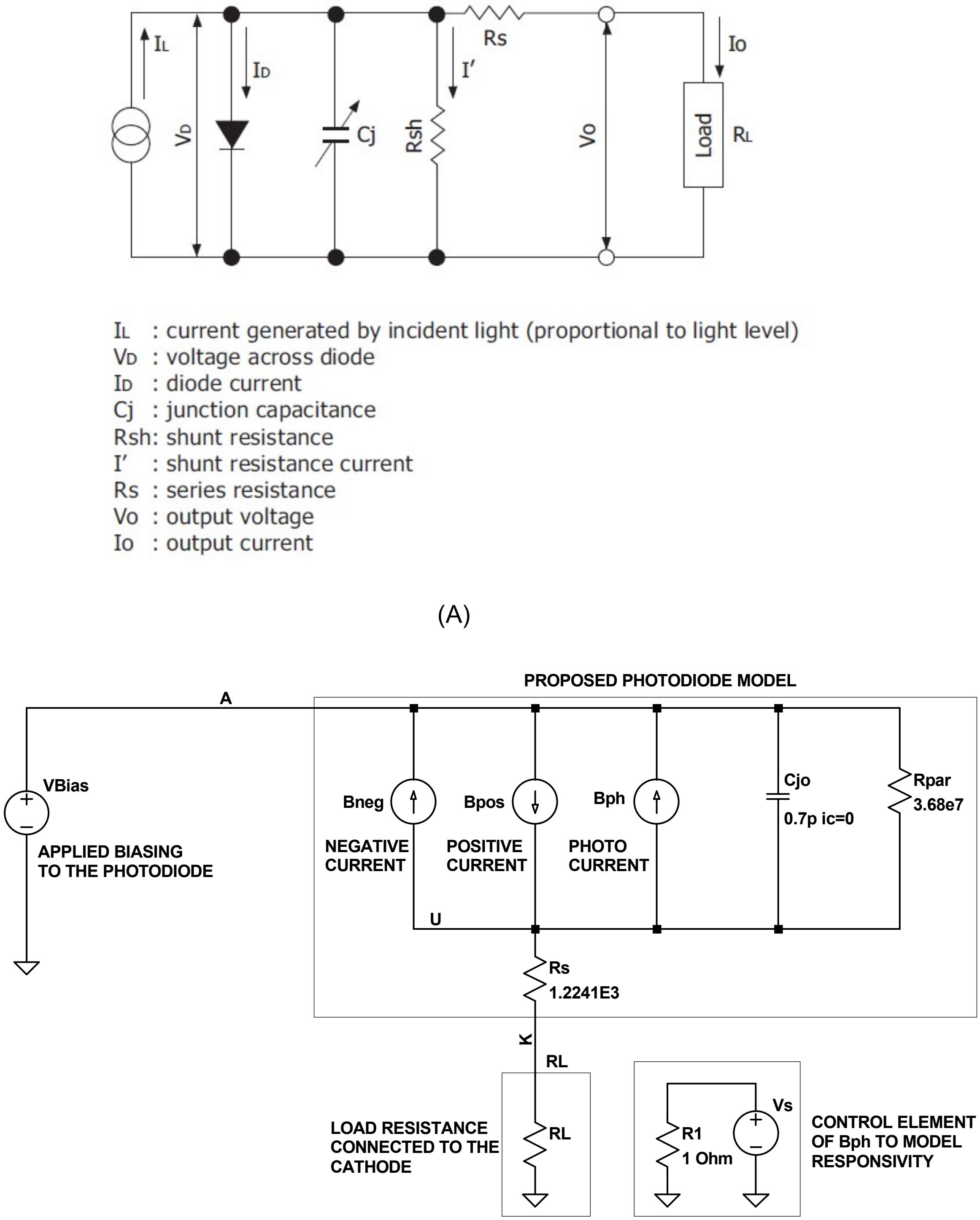

Fig. 12. Typical Photodiode Model (A) Proposed behavioral model (B).

5. Discussion

The results obtained here show that a reduced-area sensing device can be integrated in standard CMOS technology having a decent behavior, even if it has reduced break-down voltage due to the small active area and highly doped regions. The spectral response of the fabricated prototype, states the device as a good candidate for low-power, general-purpose image sensing in the visible range. However, simulation of this diode cannot be properly accomplished with the simple model of Spice, because this popular circuit simulator uses the high injection model of the diode. For simplicity, a behavioral model, obtained with both empirical and measured constants, was developed for simulation.

6. Conclusions

With this work started the characterization of an integrated photodiode which will be used in a matrix for acquisition of images in the visible range.

As a starting point, the static characterization both dark and with different light sources was addressed. The absence of a monochromator conducted to the use of a low cost characterization method which gives an acceptable idea of the overall spectral response.

Future works include the dynamic characterization to find, among others, frequency response, signal to noise ratio and dynamic range. This will need to use pulsed- or sinus modulated- light sources. Pulsed light sources could be low-cost pulsed leds or a low-power chopped laser as those already used. Sinus modulated- light sources lead to the use of a laser diode driver. Although this last solution is preferred, it requires a more expensive equipment than the first one.

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