# Analysis of Multifinger PIN Diodes Operating as Light Sensors

Gustavo Dick de Castro
*Centro Universitário FEI*
São Bernardo do Campo, Brazil
dickcastro71@outlook.com

Antonio Aurélio de Sousa Gomes
*Centro Universitário FEI*
São Bernardo do Campo, Brazil
antonio.aurelio06@gmail.com

Carla Dick de Castro Pinho Novo Gomes
*Centro Universitário FEI*
São Bernardo do Campo, Brazil
carladcpn@hotmail.com

Renato Camargo Giacomini
*Centro Universitário FEI*
São Bernardo do Campo, Brazil.
renato@fei.edu.br

Abstract—PIN diodes can be used as photodetectors in a wide wavelength range, but to know if they are good light detectors, a plenty of issues needs to be considered, like the current signal level, the responsivity and the signal-to-noise ratio. To analyze these figures of merit, simulations and experimental measurements were done, considering two different diodes. One of them has a larger intrinsic length, but a lower number of *fingers* and the other one has a smaller intrinsic length, but higher number of *fingers*. The experimental measurements were performed with the parameter analyzer Agilent 4156C and the Temperature Variation System of MMR Technology, and the simulation data was extracted through Atlas Simulator. We could verify that the number of fingers and the intrinsic length affect the device response, because it is directly linked to the current level of the devices. Therefore, we concluded that larger intrinsic length increases the absorption of photons with larger penetration depth, as well as, higher number of *fingers*, increases the absorption of photons with low penetration depth.

Keywords—photodiode, PIN, responsivity, signal-to-noise

## I. INTRODUCTION

Semiconductor materials, like silicon, have some optical properties that allow them to be good candidates concerning light sensor devices. The high possibility of one electron in the valence band jump to the conduction band leaving a “hole” where it was, make it possible. This phenomenon is called electron-hole pair generation, when electrons absorb a specific level of energy provided by the absorption of photons, so when a semiconductor material is exposed to electromagnetic radiation, the current level in the device can be measured. [1] [2]

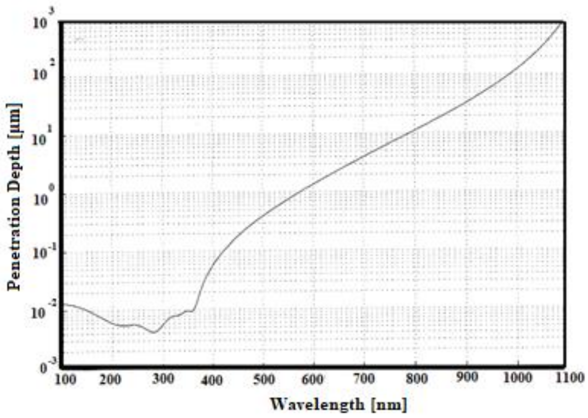
The photons, on a diode, are expected to be absorbed in the Depletion Region (DR), because this region presents lower recombination level. Besides that, the size of the DR can be enlarged by decreasing its doping concentration. That is why it is interesting to include an intrinsic region (with low doping concentration) between the P and N regions, resulting in a device named PIN diode. [3] [4]

However, another way to generate an electron-hole pair is the thermo-generation, which consists in the absorption of thermic energy, called phonon, by the electrons. This energy is latter converted into current, just like the light absorption. That is why thermo-generated current signal is considered a noise. Considering this, the size of the intrinsic region can’t be very large, but need to be larger enough to efficiently absorb the photons. [1] [2]

Moreover, another problem faced in this device is the photocurrent signal recognition. Due to the small amount of current generated by light, the diode needs to be reverse biased, so we can distinguish more easily between the thermal and photo generation. [4]

Another thing to be mentioned is the penetration depth of a photon into the silicon, which represents the medium length that a photon can penetrate on the silicon without being absorbed by an electron. Fig.1 represents the penetration depth, in micrometers as a function of the wavelength, in nanometers. [1] [2]

Fig.1 is representing the electromagnetic wave penetration depth, as a function of its wavelength. [5]




Two devices were evaluated, one with a smaller intrinsic region and a higher number of *fingers* (PIN-D), and the other with a larger intrinsic region and a smaller number of *fingers* (PIN-U). Table I presents the device’s dimensions. The diodes were produced by the research club by the MOSIS project using the 0,13 μm IBM technology, by the IMEC laboratory located on Belgium.

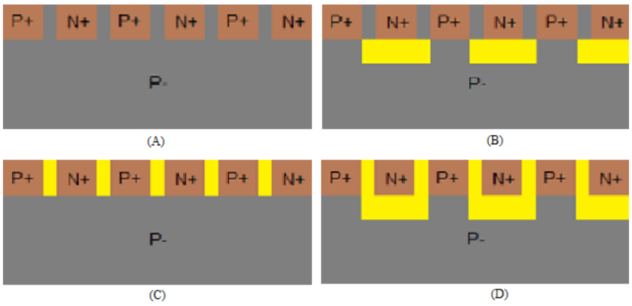
TABLE I. Devices Admeasurements

| | Li(μm) | Lp(μm) | Ln(μm) | W(μm) | *Fingers* |
|---|---|---|---|---|---|
| PIN-D | 0,3 | 3 | 3 | 270 | 84 |
| PIN-U | 1 | 3 | 3 | 270 | 69 |

Where, Li is the intrinsic region length, Lp is the positive doped region length (region with P material), Ln is the negative doped region length (region with N material), W is the device width.

To have a better understanding of the device, we plotted Figure 2, where in Fig.2A is presenting the diode with five fingers by a lateral view. Fig.2B represents the depletion region formed between N+ region and the intrinsic region (which is actually a very low doped P type region). This DR is called Vertical DR (VDR) and is located under N+. Besides that, there is another depletion region represented by Fig. 2C, called Lateral Depletion Region (LDR) and is formed between N+ and P+.,.

Fig.2. Lateral view of the diodes.




## II. DISCUSSION

The data was collected utilizing high brightness LED's as light source, their wavelengths and optical power was determined by the S2000 Miniature Fiber Optic of the Ocean Optics Enterprise.

The optical powers utilized are 0,2; 0,4 and 0,6 W/m², for blue, green, yellow and red LED's, and 10; 21 and 30 W/m² for the ultra violet LED's.

Also, the environment of the chip was a void capsule with temperature controlled by the Temperature Variation System of MMR Technology, and the measurements were performed by the parameter analyzer Agilent 4156C.

### *A. Photo-Generated Current*

In order to have a better understanding of the performance of the device concerning different radiation wavelengths, four different colors of LED's were used, that are: blue, green, yellow and red. Also, the dark current was evaluated with no incident light.

In the graphs, the squares represent the dark current, the triangles the current with blue light incidence, the triangles turned to left, the current with green light, the circles, the current with yellow light, and the lozenge represents the current with red light. Also, the empty symbols represent the PIN-U dates, and the filled ones represents the PIN-D data.

Fig.3. Anode current values of each incident light color.

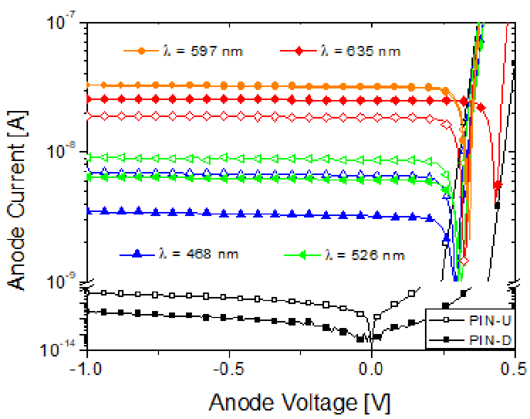



Fig.3 presents the variation of the current level as a function of the anode voltage, when the color of the incident light varies. It also has a comparison with each of the dark current.

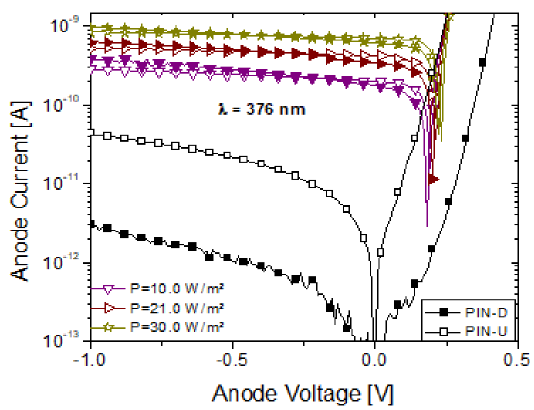
So, we can see that when the wavelength increases, the current also increases, and after a specified value of wavelength (*λ*), the current starts to decrease, which happens due to the penetration depth. When the wavelength is too low, like in the case of the blue light, the penetration depth is also low, so the photons are absorbed more superficially in the diode. In this case, there is a high probability that this superficial region contains impurities, that disturbs the absorption, also, the probability of the photons be reflected is high. In another way, with a high wavelength and consequently the penetration depth, in the case of the red light, the photon can be absorbed after the VDR, where the recombination ratio is high. So, photons that the penetration depth coincides exactly in the depletion region, are absorbed more efficiently, so, the current level is high.

Another point to note is, the current variation comparing the same color of the two devices, it's notable that with low wavelengths the PIN-U current surpass the PIN-D current, and with high wavelengths, the PIN-D current surpass the PIN-U. It happens due to the number of *fingers* and the intrinsic region size. With a larger lateral intrinsic region size, the diode will have a larger total area of LDR, and considering that the photons with low wavelength have a lower penetration depth, they are absorbed more easily in this region. On the other hand, photons with high penetration depth are absorbed more deeply in the device in the vertical intrinsic region. So, with a high number of *fingers*, and consequently, a smaller lateral intrinsic region length, photons with low penetration depth have a smaller area to be absorbed effectively, and photons with a high penetration depth have a larger one. That is probably why that the current level produced by yellow is almost the same in both, PIN-U and PIN-D. Yellow light has a penetration depth that coincides with a specific depth in the diode where both junctions (VDR and LDR) are presented at the same time.

With a comparison intent, the current level when irradiated light with wavelength of the ultra violet (U.V.) band was also collected, but with optical power of 10, 21 and 30 W/m², and Fig.4 presents the results.

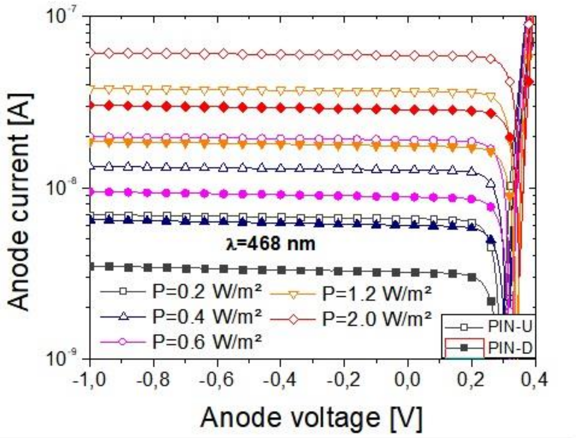
Because of the U.V. wavelength is too low, the photons are absorbed more superficially even in comparison with the blue light, so the current level is also lower. That is why we can see a small increment in the current level, when the voltage is increasing, and this one is more visible in the PIN-D. That happens due to the intrinsic region size, the smaller the intrinsic region, more easily it becomes "fully depleted", and photons have a smaller recombination ratio, so the current is higher. [6]

Fig.4. Anode current values for the U.V. light as a function of anode voltage.




If we vary the optical power of each color, the current level in the device will also varies, proportionally with the power. This happens due to the number of photons that the light source is emitting by second. If the power increases the number of photons emitted by the source also increases. This phenomenon can be seen in Fig.5.

Fig.5. Graphic representation of blue light current generation varying optical power as a function of anode voltage.




It is possible to determine this number of photons by (1).

$$N_{PHOTON} = \frac{P_{IN}}{E_{PHOTON}} \quad (1)$$

Where, $N_{PHOTON}$ is the number of incident photons in the diodes and $E_{PHOTON}$ is the energy of each photon, that is represented by (2).

$$E_{PHOTON} = \frac{hc}{\lambda} \quad (2)$$

Where, h is Planck constant, c is the light speed and λ the wavelength.

*B. Responsiveness*

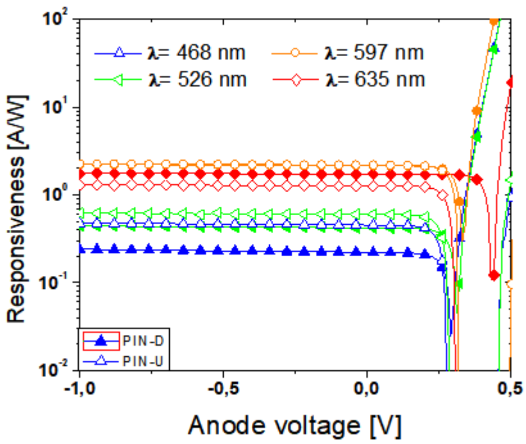
An important factor to determine the efficiency of a photodetector is the Responsiveness, that is the ratio of the photo-generated current by the incident optical power. The photo-generated current, is the difference of the current measured with incident light and with the dark current. The responsiveness is represented by (3). [7] [8]

$$R = \frac{I_T - I_{DARK}}{P_{IN}} \quad (3)$$

Where, R is the responsiveness, $I_T$ is the total measured current, $I_{DARK}$ is the dark current and $P_{IN}$ is the optical incident power. [4]

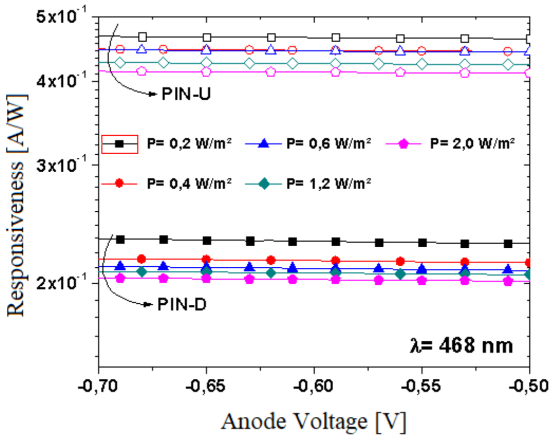
With this equation, the values measured, the power of each LED and the total area of the devices (see TABLE I), it is possible to construct a graph of the responsiveness as a function of the voltage, that is represented in Fig.6.

Fig.6. Graphic representation of the responsiveness as a function of the anode voltage.




In the Fig.6 we can see the same positioning of the curves as the Fig.3, that explains that the responsiveness in the PIN-D is larger for photons with high wavelength, because of the number of *fingers* and the large area of VDR. In the PIN-U, photons with low wavelength have more responsiveness, due to the lateral intrinsic region length, this proves the affirmation made in II.A, and quantifies it.Fig.7 represents the responsiveness with optical power variation of blue light color.

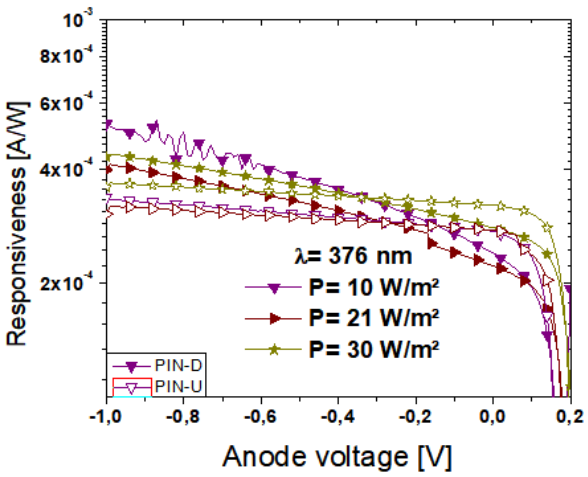
Fig.7. Graphic representation of the responsiveness of blue light varying the optical potency.




In Fig.7 we can note that for the same diode, the difference of the responsiveness in each power value, is too small, and the higher responsiveness is from the power of 0,2 W/m². The diode that presents the higher responsiveness is the PIN-U, because it provides a higher rate of photon absorption for lower wavelengths.

Fig.8 represents the U.V. responsiveness as a function of anode voltage. One can see that the performance of the device doesn't change too much considering power variation, due to the ultra-low wavelength.

Fig.8. Graphic representation of the U.V. responsiveness as a function of anode voltage




*C. Signal-to Noise Ratio*

The signal-to-noise ratio is the numeric difference of the photo-generated current and the dark current. It's a very important figure of merit to determine the efficiency of a photodetector, and is represented by (4). [7]

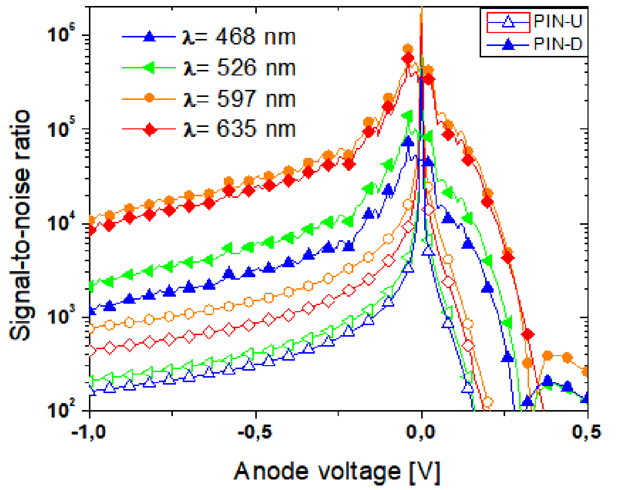
$$SNR = \frac{I_T - I_{DARK}}{I_{DARK}} \quad (4)$$

Where, SNR is the signal-to-noise ratio, $I_T$ is the total current measured on the device and $I_{DARK}$ is the dark current. [7]

Fig.10 is presenting this relation for the two diodes when we vary the wavelength with the power of 0,2 W/m².

An important thing to put in evidence is that, the larger the noise-to-signal ratio, the better the photodetector is.

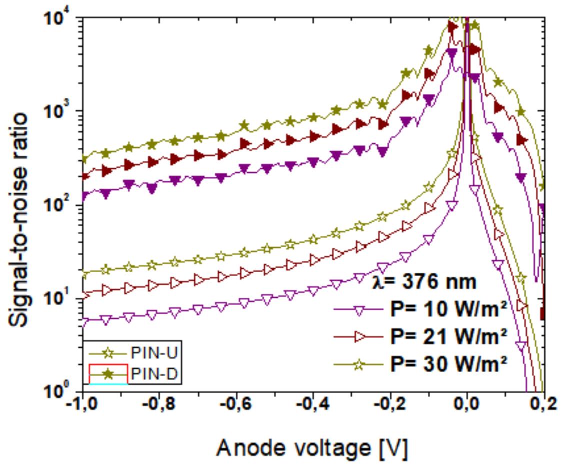
Fig.10. Graphic representation of the Signal-to-Noise ratio as a function of the anode voltage.




Considering that the PIN-D dark current is smaller than the PIN-U, the signal-to-noise ratio of the PIN-D must be larger than the PIN-U, a fact that we can see in Fig.9 that is true. Furthermore, we can see a peak in 0V, that is where the current in the device tends to zero, the diodes polarization point.

Fig.11 represents the signal-to-noise ratio of the device with U.V. illumination. We can note that it presents the same pattern of the Fig.10, with the difference that for the U.V., the responsiveness is too low compared with the other ones, what was expected, since the current in the device with U.V. is also too low.

Fig.11. Signal-to-noise rate with U.V. illumination.




## III. CONCLUSIONS

It is possible to conclude that for 325K of temperature, a device with a smaller Li, presents a larger differentiation between the photo-generated current, and dark current. This effect is due to the presence of a smaller lateral intrinsic region, which causes a reduction of the number of electron-hole pairs thermal generated. Besides that, devices with smaller Li have a larger number of fingers, which provides a higher light absorption. However, regarding these devices (with a smaller lateral intrinsic region), and consequently a lower total area of LDR, light radiation with low wavelength does not show good performance, as we could observe in the operation of PIN-D in this paper. This is due to the penetration depth of these photons be around these LDR, so with a small LDR, smaller is the performance for low wavelengths, and higher for high wavelengths. On the other hand, devices with a larger lateral intrinsic region and a smaller number of *fingers* will have a reduction of the SNR. Moreover, light radiation with low wavelength will be more effectively be absorbed, as we could observe in the operation of PIN-U device. This is because of its larger lateral intrinsic region, and consequently, a larger LDR, that provides a rise of the performance for low wavelengths, and a decrease for high ones. Therefore, the choice of the device configuration will depend on the required application, especially in terms of wavelength.

## REFERENCES

[1]. C. Novo, “Design and characterization of lateral PIN diodes-topologies, features and proposal of a new configuration”, FEI University Center, 2017, pp. 35-41.

[2]. J.P. Colinge, C.A. Colinge, “Physics of Semiconductor Devices”, Massachusetts: Kluwer Academic, 2002.

[3]. S.M. Sze, “Physics of Semiconductor Devices”, John Wiley and Sons, New York:1981, pages 743-760.

[4]. A. Afzalian, D. Flandre, “Physical modeling and Design of Thin-Film SOI Lateral p-i-n Photodiodes”. IEEE Trans. On Electron Devices, v. 52, n. 6th. Edition, 2005, pp. 1116-1122.

[5]. C.S. Júnior, S. Sasson, P.S.B. Sanches, “Science Understanding Nature”, São Paulo: Saraiva S A, 2009.

[6]. C. Novo, R. Buhler, J. Baptista, R. Giacomini, A. Afzalian, D. Flandre. “Quantum Efficiency Improvement of SOI p-i-n Lateral Diodes Operating as U.V. Detectors at High Temperatures”. IEEE Sensors Journal, v. 17, p. 1641-1648, 2017.

[7]. C. Novo, “Design and characterization of lateral PIN diodes-topologies, features and proposal of a new configuration”, FEI University Center, 2017, pp. 66-67.

[8]. C. Novo, R. Zapata, R. Giacomini, “Optimization of PIN photodiodes regarding responsiveness and quantum efficiency”. In: Great ABC Research Symposium, São Bernardo do Campo. 2014.