

# ANALYSIS OF PHOTOCURRENT AND QUANTUM EFFICIENCY OF PIN BULK CMOS AND PIN SOI CMOS PHOTODIODES

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## ABSTRACT

The photodiodes are the most important devices in an image sensor. Their answer depends on several factors, such as wavelength, the refraction index of materials, the width of the depletion region, the substrate doping and device dimensions. In this article, the responses of the BULK PIN photodiode and SOI PIN photodiode are compared. Through the comparison among the photogenerated current of the devices, it was possible to conclude that the quantum efficiency is dependent on the incident wavelength, the dark current, the recombination effect, the photosensitive area, and the reflections. An analysis of the effects produced by the change of the incident power intensity was done either.

**Keywords:** photodiode, dark current, quantum efficiency.

## 1. INTRODUCTION

Nowadays there is an increasing need for image sensors with fast response, high quantum efficiency, and low dark current. These characteristic are important so they can be suitable for different purposes, such as optical communications, where non integrated detectors are usually employed, since the particular indirect energy band properties of silicon make this semiconductor not very efficient for the optical reception at 850nm wavelength [1-3]. However as Si is the most widely used and low-cost semiconductor material in electronics, there is a great interest to integrate such receivers.

The conventional bulk CMOS technology had already been used in many applications [3], but, up to now, few studies have considered the use of silicon-on-insulator (SOI) technology, because it presents considerable difficulty for the photosensor implementation with standard logic fabrication processes. Though, solutions have been proposed to implement the photosensors in the SOI substrate underneath [4] or on top of the circuits by a postprocessing step, e.g., the deposition of amorphous TFA (thin film on ASIC) photodiodes [5]. Other solutions exist using lateral bipolar phototransistors [6], which can be combined for a further increase of their sensitivity with backside illumination using silicon-on-sapphire substrate [7]. Unfortunately, these solutions have more costly prices and more complex fabrication processes.

An efficient alternative to absorb a wider range of wavelengths with Si-based devices is to implement PIN lateral photodetectors, using standard process flows [5].

In this work, photodetection in PIN diodes will be analyzed through two-dimensional numerical simulations of the devices performed with Atlas Software [8].

Aiming to investigate the performance of the lateral PIN BULK CMOS and lateral PIN SOI CMOS photodiodes, illumination sources since  $\lambda=200$  nm, up to IR ( $\lambda=1000$  nm) wavelengths were considered.

## 2. PHOTODIODES CHARACTERISTICS

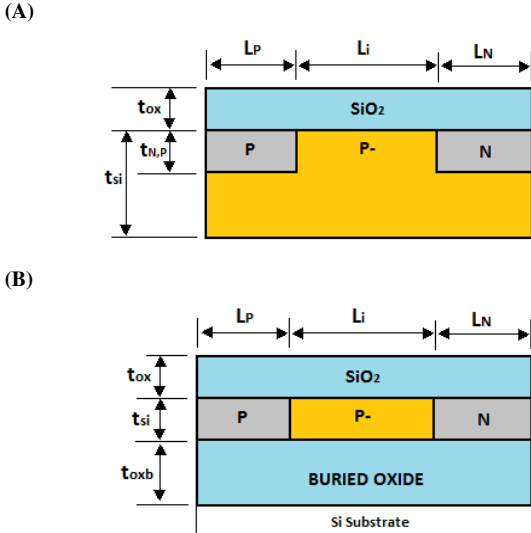
The process of semiconductor light absorption occurs when the incident light produces quantum level transitions of electrons to higher energies [9]. This way, the carriers can be generated, and they can contribute to the device current if the hole-electron pairs do not recombine, but are quickly separated by the action of an electric field. This photocurrent increases the reverse current of a reverse biased diode.

For high speed operation, the depletion region should be kept thin enough, in order to reduce the transit time of photogenerated carriers [10]. However, to increase the quantum efficiency (defined as the number of carriers generated by incident photon), the width of the depletion region has to be thick enough to allow a greater fraction of the incident light to be absorbed. So there is a tradeoff between response speed and quantum efficiency.

Figure 1 presents a schematic cross-section of the studied devices, indicating thicknesses and other important dimensions. The dimensions were chosen considering contact and metal minimum limitations by the MOSIS SCMOS Rules [11] and are shown in table 1.

**Table I:** Device Parameters

Parameter	BULK PIN	SOI PIN
Silicon film thickness ( $t_{Si}$ )	800nm	80nm
Buried oxide thickness, ( $t_{oxb}$ )	X	390nm
Passivation oxide thickness ( $t_{oxp}$ )	280nm	280nm
Intrinsic doping concentration ( $N_i$ )	$3 \times 10^{16} \text{ cm}^{-3}$	$3 \times 10^{16} \text{ cm}^{-3}$
P region doping concentration ( $N_A$ )	$1 \times 10^{20} \text{ cm}^{-3}$	$1 \times 10^{20} \text{ cm}^{-3}$
N region doping concentration ( $N_D$ )	$1 \times 10^{20} \text{ cm}^{-3}$	$1 \times 10^{20} \text{ cm}^{-3}$
P, N regions length ( $L_{P,N}$ )	4,5 $\mu\text{m}$	4,5 $\mu\text{m}$
Intrinsic Length ( $L_i$ )	9 $\mu\text{m}$	9 $\mu\text{m}$
P, N regions thickness ( $t_{p,n}$ )	300nm	80nm

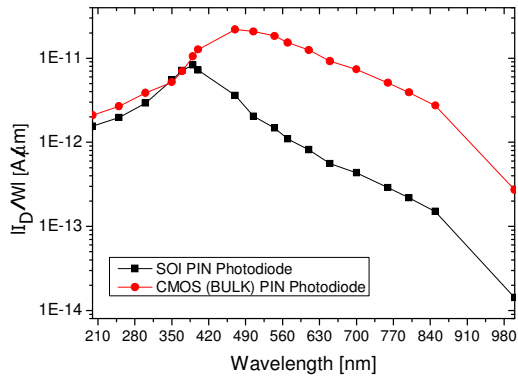


**Figure 1:** Cross-section of the studied devices (A) One finger of PIN BULK CMOS lateral photodiode (B) One finger of PIN SOI lateral photodiode

### 3. RESULTS

Figure 2 presents the normalized photodiode current as a function of wavelength for SOI and CMOS BULK PIN photodiodes. For  $\lambda$  greater than around 400nm, the photocurrent decreases as wavelength increases, this fact takes place because greater wavelengths have smaller energy.

As can be noted, this fact does not occur for wavelengths smaller than 400nm, because the absorption of light in semiconductors varies according to its thickness. Silicon devices absorb light as a function of their thickness for wavelengths ( $\lambda$ ) up to 1100 nm [9]. Blue light, however, is absorbed close to the surface in silicon. For instance, for  $\lambda=400$  nm the absorption depth is close to 0.06  $\mu\text{m}$  [9,12]. Therefore, wavelengths smaller than around 400nm will be absorbed next to the surface, where recombination velocity ranges from  $10^2$  to  $10^5$  cm/s [13], depending on the cleanliness and passivation of the crystal surface.



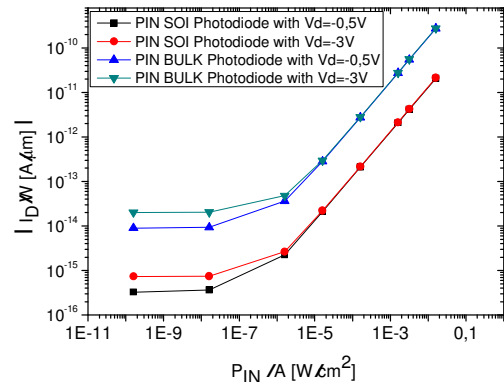
**Figure 2:** Normalized photodiode current under illumination as a function of wavelength for SOI and CMOS BULK PIN photodiodes with  $L_i=9\mu\text{m}$  and  $L_{P,N}=4,5\mu\text{m}$  for applied voltage of  $V_d=-0,5V$ .

Semiconductor crystals are of the highest purity and

quality, but they are not perfect. They contain some crystal defects such as interstitials, vacancies, and dislocations, as well as traces of impurity elements such as metallic atoms or oxygen. These defects and impurities give rise to permitted levels within the energy band gap, that are called “recombination centers” and in the surface is indeed a place where the periodicity of the crystal lattice is interrupted, and where contact with another substance (air, SiO<sub>2</sub> and metal) is made. As a result, for smaller wavelengths, the photocurrent will be smaller than expected, because the recombination mechanism is much more pronounced at the surface.

Figure 2 also shows that for almost the entire range of wavelengths (except for  $\lambda$  around 400nm), the generated photocurrent for the Bulk PIN Photodiode is greater than for SOI. This happens because for Bulk PIN Photodiode, the vertical depletion layer has to be taken into account, and for SOI devices, the lateral depletion layer is the only one that contributes to the photocurrent.

Another valid observation is that for SOI PIN photodiodes, the greater  $I_D$  is obtained when illuminated with  $\lambda=400$  or 390nm. Furthermore, no more than a few tens of nanometers are required for the absorption layer. This allows higher UV (ultra-violet) selectiveness [14,15] for lateral photodiodes in SOI compared to bulk. However, as wavelength increases, and  $\alpha$  (absorption coefficient) decreases, an increasing part of the light passes through the I-layer without being absorbed and consequently lowers the Quantum efficiency for SOI devices. This light is absorbed in the substrate for BULK photodiodes, but in SOI, due to the presence of the buried oxide (BOX), the generated charges have no chance to diffuse from the substrate to the intrinsic layer. This allows faster lateral photodiodes in SOI compared to bulk by avoiding the slow and less selective diffusion current [16].



**Figure 3:** Absolute normalized photocurrent as a function of the incident optical power intensity per unit of area for SOI and BULK PIN photodiodes extracted at  $V_D=-0,5V$  and  $V_D=-3V$ .

In Figure 3, the normalized photocurrent is plotted as a function of  $P_{IN}/A$  and it can be noted that, as  $P_{IN}$  increases, the generated photocurrent increases as well. However, SOI PIN diodes present lower current than the BULK because of the additional vertical depletion layer presented by BULK devices (as mentioned before).

The presented results also show that  $I_D$  is not so strongly

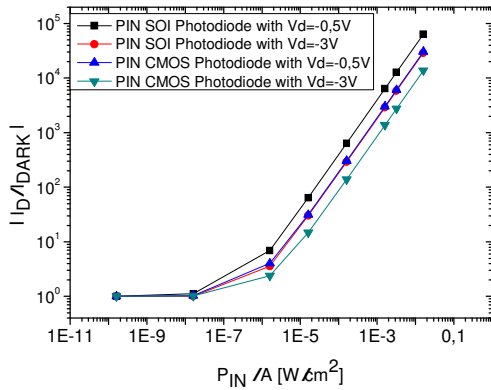
dependent on the optical power intensity when  $P_{IN}$  is lower than about  $1E-7$  W/cm<sup>2</sup>, because the current is virtually entirely provided by the dark current.

Apart from a large signal, low noise is also important as it will ultimately determine the minimum detectable signal strength. There are many factors that contribute to noise, as seen, the dark current, that is the leakage current when the photodetector is under bias but not exposed to the light source, and it is due to thermal generation of electron-hole pairs in the depletion region.

Bulk devices exhibit a dark current greater than SOI because they have a vertical depletion layer beyond the lateral one.

For both SOI and BULK pin photodiodes, the dark current is proportional to the length of depletion layer and consequently to the applied voltage. Figure 3 shows that for smaller values of  $V_D$ ,  $I_{DARK}$  increases, as a result of the increased size of the depletion layer.

Despite having lower photogenerated current, SOI devices present better results than BULK when the ratio between photocurrent and dark current is considered. This fact can be clearly seen in Figure 4, where this ratio is presented as a function of  $P_{IN}$ . One can see that for higher values of  $V_D$ , the ratio of  $I_D/I_{DARK}$  increases.



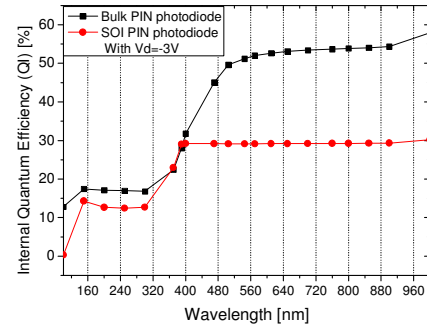
**Figure 4:** Photocurrent normalized by  $I_{DARK}$  as a function of the incident optical power density for SOI and BULK PIN photodiodes extracted at  $V_D=-0,5V$  and  $V_D=-3V$ .

A major figure of merit for photosensitive devices is their Quantum efficiency [9] defined as:

$$(1) \quad QE_{TOTAL} = \frac{I_{ph}}{I_{phMAX}} = \frac{P_{abs}}{P_{IN}} * \frac{A_{ph}}{A_{total}} * QI$$

where  $I_{ph}$  is the photogenerated anode current through the diode and its maximum value ( $I_{phMAX}$ ).

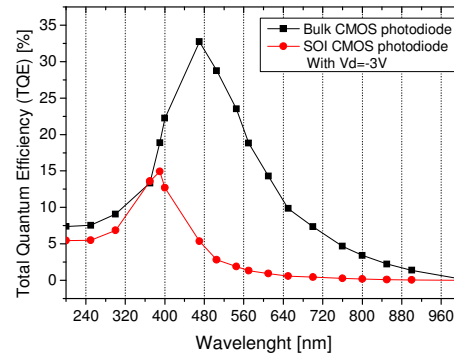
The total quantum efficiency is limited by three kinds of losses: 1) The photosensitive area ( $A_{ph}$ ), because some part of the total area ( $A_{total}$ ) can be considered as optically inactive, as the part covered by metal electrodes; 2) Reflection and Transmission, because not all the  $P_{IN}$  (optical power density impinging the photodiode) is absorbed by the device ( $P_{abs}$ ) and 3) The losses between carriers collected compared to those generated in the absorption region. The internal quantum efficiency (QI) accounts for the losses by recombination.



**Figure 5:** Internal Quantum Efficiency of SOI and BULK PIN Photodiodes as functions of wavelength for a reverse bias of  $V_D=-3V$ .

As shown in Figure 5, for  $\lambda$  greater than 400nm, the internal quantum efficiency is higher for longer wavelengths in BULK devices, while for SOI, it remains almost without variation. It is due to the charges generated outside the depletion region, in quasi-neutral material: they have to diffuse to the high field region in order to be separated and to contribute to the photocurrent. It is also important to say that the diffusion current, is a slow process, which can degrade the bandwidth of the BULK devices. In SOI detectors, this effect of slow diffusion is reduced owing to the presence of the buried oxide, but, on the other hand, the absorption thickness is limited by the silicon film thickness.

For  $\lambda$  smaller than 400nm, as already seen, the surface recombination effects take place, and internal quantum efficiency is degraded.



**Figure 6:** Total Quantum Efficiency of SOI and BULK PIN Photodiodes as a function of wavelength for a reverse bias of  $V_D=-3V$ .

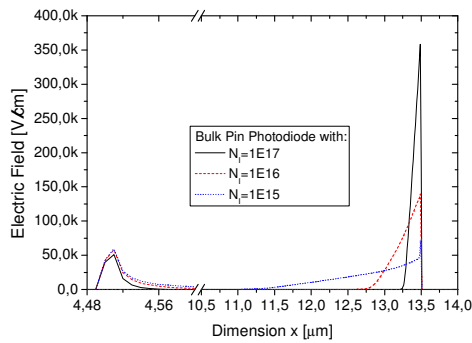
The total quantum efficiency is shown in Figure 6. This parameter is limited by the reflections and transmission losses, which are different for SOI and BULK photodiodes, since the light has to travel through several thin layers with different optical properties, and due to the difference in the index of refraction between each material, a part of the beam is transmitted and a part is reflected. As the layer structure in SOI and BULK is different from each other, the reflections and transmission systems are different either.

Another kind of loss that has to be taken into account is the photosensitive area, but as the two simulated devices have the same photosensitive areas, this effect can be

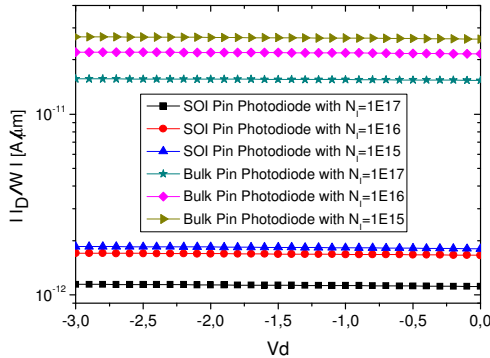
neglected when comparing their total quantum efficiency. Through Figure 6, the favorable behavior for SOI Pin showed for  $\lambda$  around 400nm is clear.

For  $\lambda$  smaller than 400nm, the Total QE of the two photodiodes is very close to each other because it is limited by the surface recombination event. But, for  $\lambda$  greater than 400nm, the distance between the Total QE increases due to reflection and carrier diffusion mechanism. BULK devices have their maximum value of QE around 470nm, while SOI have the maximum value for  $\lambda$  at 390nm.

Another issue studied in this paper is the photodetector's response due to change of the P' substrate dopants concentration ( $N_I$ ). The intrinsic region, corresponding in fact to a P- doping, is not necessary fully depleted and two depletion layers have to be considered depending on the  $N_I$  parameter, as can be seen in Figure 7, where the electric field is plotted as a function of the dimension x of the devices.



**Figure 7:** Electric Field as a function of Dimension x for BULK PIN photodiodes with  $V_d=-3.3V$  for different  $N_I$ .



**Figure 8:** Normalized photocurrent as a function of  $V_d$  for SOI and BULK PIN photodiodes with different  $N_I$  concentration illuminated at  $\lambda=545nm$ .

In Figure 8, it is shown that the photocurrent of the devices increases when the intrinsic concentration decreases. It is due to the width of depletion regions, which becomes wider as  $N_I$  decreases. This effect is observed in both devices.

#### 4. CONCLUSION

It was presented that the effect of deep carrier diffusion appears for bulk devices for wavelength greater than about 400nm, so the total quantum efficiency is greater,

almost 33% for  $\lambda=470nm$ . However, this is a slow mechanism that results in the so-called "long-tails" in the impulse response and severely degrades speed performances. PIN diode associated to bulk technology showed to be the best choice for sensors where sensitivity in a wide range is the most important requirement.

From the evaluation results, it was proved the UV favorable behavior for SOI PIN, showing the total quantum efficiency of 15% without any anti-reflective coatings. However, the buried insulator (BOX) presented in SOI devices, limits the photon absorption depth of the photodiodes. The main consequence is that the association of lateral PIN and SOI technology presented the best result for wavelengths smaller than 400nm, but the quantum efficiency above this range decreases significantly. It is worth noting that this range depends on the silicon film thickness.

#### 5. ACKNOWLEDGEMENTS

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