Temperature, Silicon Thickness and Intrinsic Length Influence on the Operation of Lateral SOI PIN Photodiodes

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Abstract— **This work presents an analysis of the influence of intrinsic length region and the thickness of the silicon film on the performance of lateral thin-film SOI PIN (Silicon on insulator P-I-N photodiodes) when illuminated by low wavelengths, in the blue and ultraviolet (UV) range. The experimental measurements performed with the wavelengths of 396 nm, 413 nm, and 460 nm in a temperature range of 100 K to 400 K showed that the optical responsivity of the SOI PIN photodetectors has larger dependence on the incident wavelength than on the variation of temperature. Two-dimensional numerical simulations showed the same trends as the experimental results as a function of temperature and as a function of wavelength. Numerical simulations were used to investigate the responsivity and total quantum efficiency of PIN SOI photodetectors with intrinsic length region ranging from 5 μm to 30 μm and silicon film thickness ranging between 40 nm to 500 nm. From the results it can be concluded that by properly choosing intrinsic length and silicon film thickness it is possible to optimize PIN SOI photodiodes performance for detecting specific wavelengths that can help defining the best technology for detection of a given wavelength.**

Index Terms— **Silicon-on-insulator, PIN diodes, Photodetector, Responsivity, Total quantum efficiency.**

I. INTRODUCTION

The incidence of light in semiconductor devices such as photodiodes promotes electron-hole generation. If such devices are reversely biased, the electric field separates the electron-hole pairs generated in the depletion region, and these carriers are collected in the diffusion regions, giving rise to the photocurrent [1]. The width of the depletion region plays an important role in this process. It must be large enough to absorb a significant amount of incident photons, for the generation of electron-hole pairs and to increase the photocurrent, and also be small enough to allow for electron-hole pairs to be collected in the diffusion region, which decreases the photocurrent.

A special case of the PN junction photodiode is the PIN diode which is one of the most common photodetectors [7], since the intrinsic depletion region can be adjusted to optimize the quantum efficiency and frequency response. The PIN diode consists of a PN junction separated by an intrinsic (I) region, with an intrinsic length region (L_i) [1], as shown in Figure 1. In practice, the intrinsic region may correspond to either a P-type or N-type region with a low doping level (in the order of 10^{15} cm^{-3}).

The absorption of light varies with the penetration depth into the material [4]. Lateral PIN SOI photodiodes implemented in thin silicon films, are efficient alternatives for the absorption of short wavelengths [4]. For example, UV and blue light penetration depths in silicon are around 100 nm and 500 nm, respectively [1]. The control of the width of the intrinsic region in PIN photodiodes can be adapted to optimize
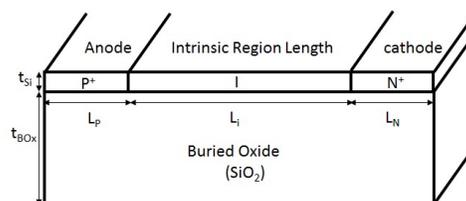

Fig.1 Lateral PIN SOI photodiode structure

quantum efficiency and responsivity [1]. Also, by having the silicon film in the top of a buried oxide layer, promotes isolation between the photogenerated carriers and the substrate, which reduces the device dark current, improving its efficiency, and low capacitance, also increasing the frequency response [5]. This also allows for the integration of photodetectors with CMOS circuits. These characteristics contribute to optical power measurements through the detection of short wavelengths (λ) in the range of blue and UV, in the spectral range below 400 nm. They are widely used in various applications such as in the environment [3], measurements of UV and ozone rates, measurement of DNA concentration, detection of bacteria [4], and on high-density DVDs that operate with a wavelength of 405 nm [5].

In this work, the operation of lateral SOI PIN diodes for the detection of short wavelengths are investigated in the range of blue and ultra-violet (UV), in a wide temperature range. The goal is to deepen the study of the efficiency in the lateral SOI PIN photodiodes for short wavelengths taking into account the variations of the intrinsic region length and the silicon film thickness as a function of temperature. The appropriate choice in the dimensions of the silicon film thickness and the intrinsic length region will help in the optimization of device design and fabrication. The analysis of these devices is performed through experimental data and two-dimensional numerical simulations, aiming at performance improvement for photodetection of short wavelengths.

II. EXPERIMENTAL MEASUREMENT RESULTS

Diode current (I_D) as a function of applied voltage (V_D) curves at different temperatures and incident light sources have been obtained using the Variable Temperature Micro Probe System from MMR Technologies and the Agilent 4156C Semiconductor Parameter Analyzer [6], with grounded substrate.

A. Photodiode Characteristics

Multifingered lateral SOI PIN diodes were implemented following the process described in [6]. The device's technological and geometrical parameters of the photodiode used in

this work are presented in Table I. Figure 2 presents an optical microscope image of part of an interdigitated PIN SOI lateral photodiode measured. All samples present an anti-reflection coating.

B. Light Sources Characteristics

The I-V curves of the experimental photodiode have been measured both in the absence of light and when illuminated with three different wavelengths (λ), from near UV (396 nm), Violet (413 nm) and Blue (460 nm), provided by different LEDs. The light source intensity of each LED has been measured using spectrometer USB645, from Ocean Optics. The obtained total power intensity measured at 50 mm from the light source is presented in Table II. This is the distance between the bare chip and the source light in the microprobe during the electrical measurements.

Table I. Lateral SOI PIN diodes parameters.

Parameter	Unit	Dimension
Silicon film thickness (t_{Si})	nm	80
Buried oxide thickness (t_{BOx})	nm	390
Intrinsic region doping concentration (N_{AI})	cm^{-3}	10^{15}
P+ region doping concentration (N_A)	cm^{-3}	2×10^{20}
N+ region doping concentration (N_D)	cm^{-3}	4×10^{20}
Intrinsic region length (L_i)	μm	9
P+ region length (L_P)	μm	9
N+ region length (L_N)	μm	9
Total width (W)	mm	55
Total area	mm^2	1
Depletion region extension @ V_D = 0V	μm	1.1
Depletion region extension @ V_D = -1.5V	μm	1.8

Fig. 2 Optical microscope top view of an interdigitated PIN SOI lateral photodiode used in this work [10].

Table II. Power intensity of light sources measured at 50 mm of distance.

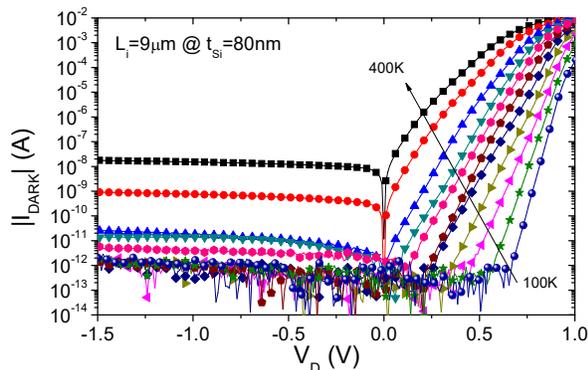| Wavelength (nm)		P_{IN}/A (mW/cm^2)	P_{IN} (W)
396	UV	0.783	7.83 ×10^{-6}
413	Violet	0.464	4.64 ×10^{-6}
460	Blue	0.696	6.29 ×10^{-6}

Fig. 3 Absolute dark current measured for temperatures between 100K and 400K, as a function of the applied voltage.

C. Experimental Results

The measured photodiode current (I_D) under a given applied voltage represents the sum of the photocurrent (I_{PG}), due to the incident light power on the device, and its dark current (I_{DARK}), that is the current in absence of light, due to thermal generation (1).

$$|I_D| = |I_{PG}| + |I_{DARK}| \tag{1}$$

The absolute dark current (I_{DARK}) as a function of the applied voltage, measured in the absence of light, is presented in Figure 3 for temperatures ranging from 100 K to 300 K, with 25 K steps. I-V curves at 350 K and 400 K are also presented. As presented in this figure, the rise of temperature increases the dark current (I_{DARK}) in several orders of magnitude as a result of increased thermal generation of electrons [2]. For temperatures below 300 K, however, the dark current reduces to levels below the minimum limit of the characterization system. Also, for V_D smaller than –0.5 V, I_{DARK} remains practically constant, showing that the electric field has little influence in the dark current, as presented in Figure 4, that shows the dark current per width as a function of temperature.
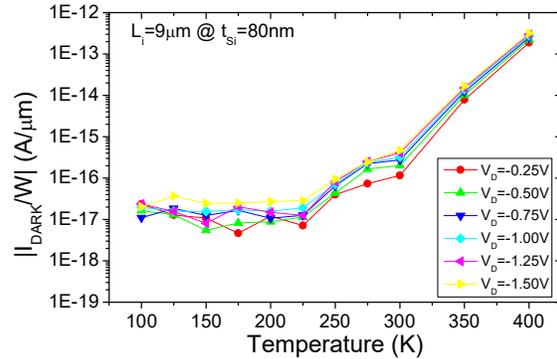

Fig 4 Normalized absolute dark current as a function of temperature measured at different applied voltages.

The normalized absolute total photodiode current ($|I_D/W|$) is presented as a function of T under UV, violet and blue illumination is presented in Figure 5. As reported in [6], different physical effects take place depending on the temperature, first increasing the current with temperature rise (due to reduction of bandgap narrowing) and then reducing at moderately high temperatures (due to mobility degradation). Since the light sources have different power intensities, it is possible to note different photogenerated current levels. However, although the available blue light has shown higher power intensity, violet source resulted in larger current. It indicates that the photogenerated current depends not only on the power intensity but also on the incident wavelength.

The responsivity and quantum efficiency under UV, violet and blue light sources as a function of temperature is presented in Figure 6. From these results, one can note that the responsivity of the studied SOI PIN diode becomes higher as the wavelength decreases. In the presented temperature range, under UV illumination the mean responsivity is around 82 mA/W with a variation around 18 %, while it is around 32 mA/W under violet illumination and 20 mA/W for the blue light source. The reduced responsivity to blue light explains the smaller current seen in Figure 5(C). The total

quantum efficiency has an identical response compared to responsivity and has an efficiency around 27 % when the device is under UV light and reduces when the wavelength is increased [7].
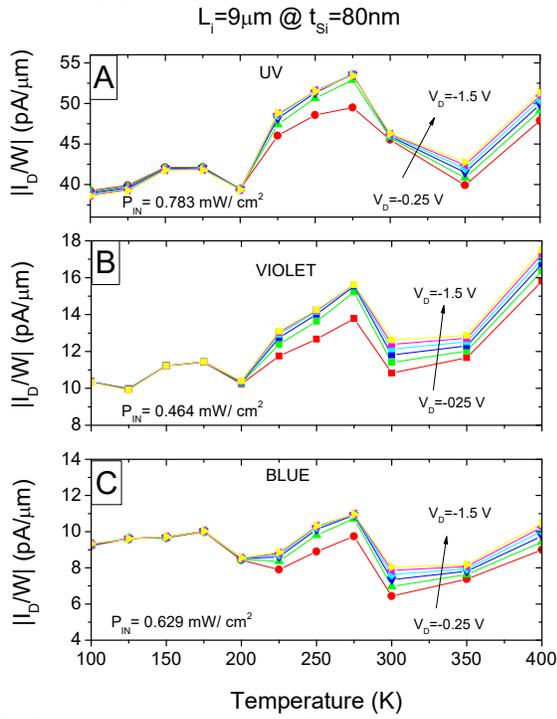

Fig 5 Normalized total current as a function of temperature measured at different applied voltages and three different light sources.
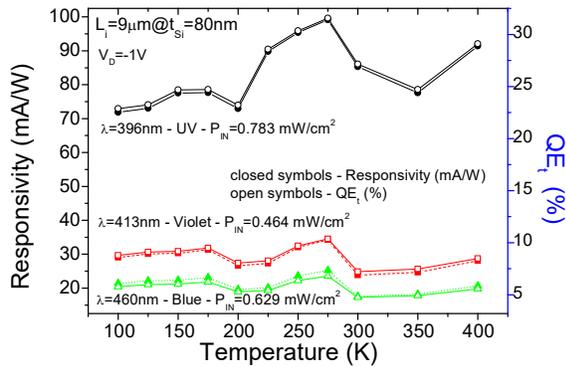

Fig. 6 Responsivity and total quantum efficiency under different light sources, as a function of the temperature for the studied photodiode.

III. TWO-DIMENSIONAL NUMERICAL SIMULATIONS

Aiming at extending the experimental analysis for different geometrical and technological parameters, two-dimensional numerical simulations of thin-film SOI PIN lateral photodiodes were performed with Atlas software [8]. The simulation models were based on the results of [10] and account for mobility (μ) dependence on doping concentration (N), temperature, and electric field, bandgap narrowing and Auger and SRH recombination, doping and temperature-dependent lifetime and incomplete carrier ionization for the lightly doped region at low temperatures.

The geometrical and technological parameters are the same as the one presented in Table I unless it is mentioned otherwise. For all simulations, W = 1 μm.

A. Temperature Effects

The photodiode current has been simulated for temperatures ranging between 100 K and 400 K for and is presented in Figure 7 as a function of the wavelength (λ) for L_i = 8 μm and P_{IN} = 1 mW/cm^2. It can be seen that starting from λ = 200 nm, the current increases linearly with wavelength up to 370 nm [9], named as wavelength cutoff (λ_c) [1]. Further increases of λ above λ_c causes the reduction of photogenerated current. It is related to the absorption of light in the semiconductor, which in this case remained 100 % for λ up to λ_c, reducing after that. For wavelengths larger than λ_c the energy of photons in the thin-film silicon layer is smaller, and a smaller amount of electron-hole will be generated. It is also possible to note that the absorption has shown to be independent on the temperature in the studied range.

The normalized photocurrent ($|I_{PG}/W|$) calculated by (1) is shown in Figure 8 under UV, violet and blue illumination, as a function of temperature. The photocurrent increased with temperature, but a reduction for T > 300 K is seen, due to the significant increase in the dark current.

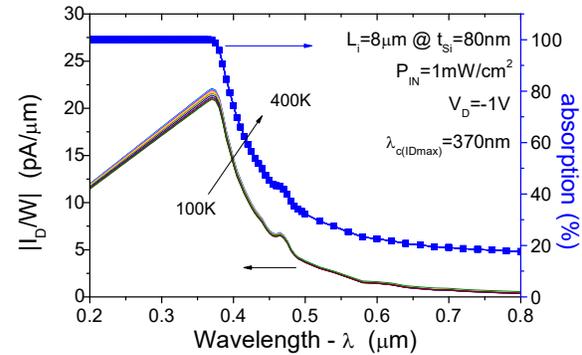Fig.7 Normalized absolute total current, I_D as a function of wavelength, λ for the temperature range of 100K to 400K for photodiode with L_i=8μm.
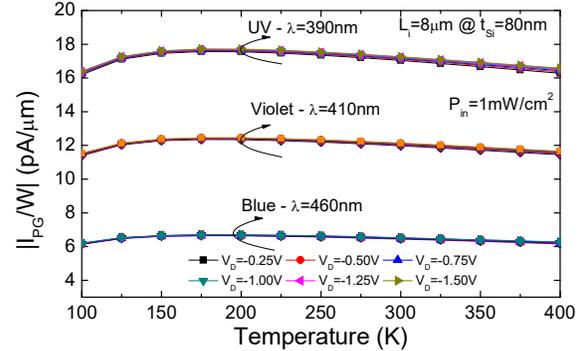

Fig. 8. Normalized absolute photocurrent, $|I_{PG}/W|$ under UV, violet and blue illumination, as a function of the temperature for photodiode with L_i=8μm.

The dark current (I_{DARK}) simulated at temperatures below 300 K showed values around 10^{-16} A, due to the lower limit of the simulator numerical accuracy. On the other hand, an increase of 4 orders of magnitude have been observed when increasing the temperatures to 400 K.

The responsivity and total quantum efficiency were also calculated and have shown to be like the results observed for the experimental data. The average values of simulated quantum efficiency for UV, violet and blue illumination are 21%, 13%, and 7% respectively, while the experimental mean values were about 27%, 8.5%, and 6%. It is worthwhile men-

tioning that model parameters were not adjusted to fit the experimental data.

B. Influence of Intrinsic Length

In order to evaluate the behavior of the PIN photodiodes taking into account the variations of the intrinsic length region (L_i), simulations of photodiodes were performed with L_i ranging between 5 μm and 30 μm. Figure 9 shows the results of the normalized total current, $|I_D/W|$ as a function of wavelength, obtained for these photodiodes. The increase of the intrinsic length region causes an increase of the photocurrent. However, the maximum absorption occurs at the same wavelength cutoff λ_c (around 370 nm).
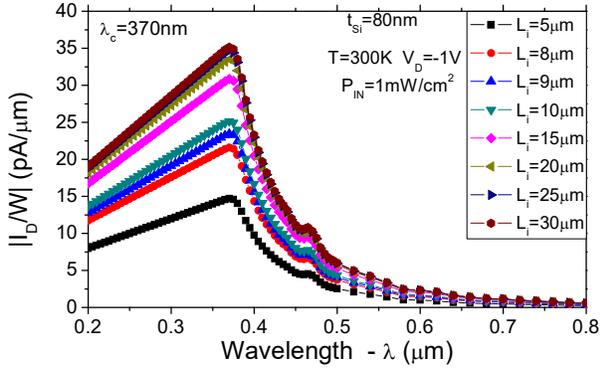
Fig. 9 Normalized absolute total current, $|I_D/W|$ for photodiodes with different intrinsic length, as a function of the wavelength.
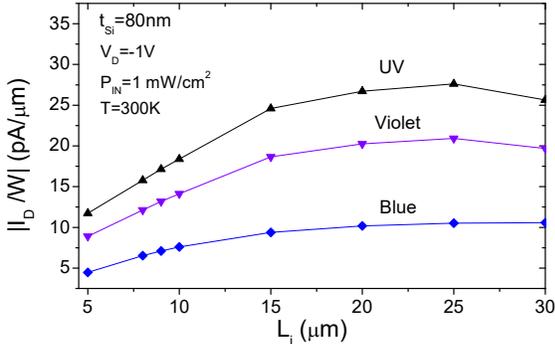

Fig. 10 Normalized absolute total current $|I_D/W|$ under UV, violet and blue illumination, as a function of intrinsic length.

Figure 10 shows the normalized total current as a function of intrinsic length for the three simulated wavelengths. The increase in the intrinsic length region increases the photosensitive area, which contributes to the photocurrent increase. However, the increase of intrinsic region length causes an increase of the distance to be traveled by the electron-hole pairs generated towards the diffusion region, favoring recombination. That is the reason for the photocurrent decrease for $L_i >$ 25 μm.

The responsivity and total quantum efficiency are presented as a function of the intrinsic length region in Figure 10, for all simulated photodiodes. It is possible to notice that the point of maximum responsivity and quantum efficiency remains the same for any wavelength and is around 13.6 μm, indicating a possible optimal intrinsic length for the simulated set of technological parameters.

C. Influence of Silicon Film Thickness

Aiming to analyze the performance of SOI PIN lateral diodes implemented in different SOI technologies, silicon film thickness has been also varied through the simulations. Silicon layer has been varied between 20 nm and 1 μm, ranging between thin to thick SOI, with L_i = 5 μm. It is important to mention that down to t_{Si} = 20 nm, no quantum effects are expected, which are out of the scope of this work.
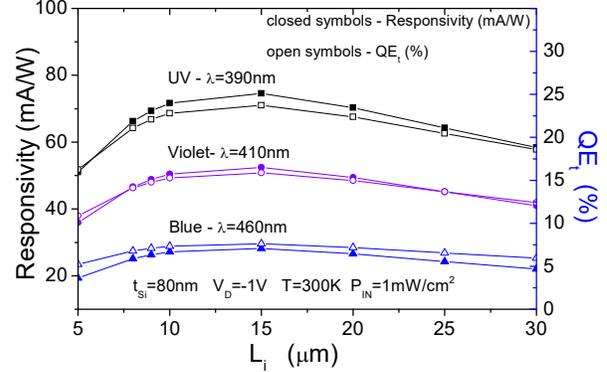

Fig. 11 Responsivity and total quantum efficiency under UV, violet and blue illumination as a function of intrinsic length region.
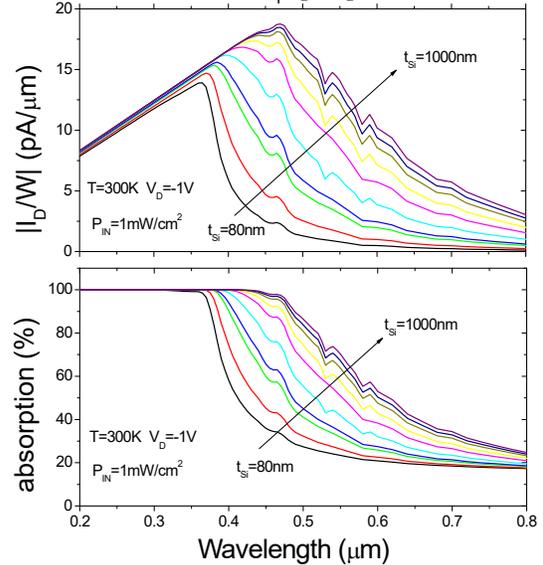

Fig. 12. Normalized absolute total current, $|I_D/W|$ and absorption for different silicon film thickness (t_{Si}) as a function of wavelength (λ) for photodiode with L_i=5μm.

Figure 12 presents the normalized absolute total current, and absorption for different silicon film thickness (t_{Si}) as a function of wavelength (λ). It is well known that the generation and absorption of electron-hole pairs occurs at the surface of the silicon for small wavelengths. On the other hand, longer wavelengths are absorbed deeper in silicon layer. Therefore, each silicon film thickness features a different wavelength cutoff, as presented in Figure 13. A linear relation between λ_c and t_{Si} can be seen.

Figure 14 shows the normalized absolute total current, $|I_D/W|$ under UV, violet and blue illumination, as a function of silicon film thickness. From these results one can note that thinner silicon layers already reach the maximum current for shorter wavelengths. For instance, for UV absorption, silicon layers thicker than 300 nm do not contribute to photogeneration. For violet light, the maximum current level is reached

for t_{Si} = 500 nm, whereas blue light has shown to be absorbed even above 1 µm. Above these values, the increase in silicon volume due to the increase in silicon thickness does not imply a significant increase in the total current.
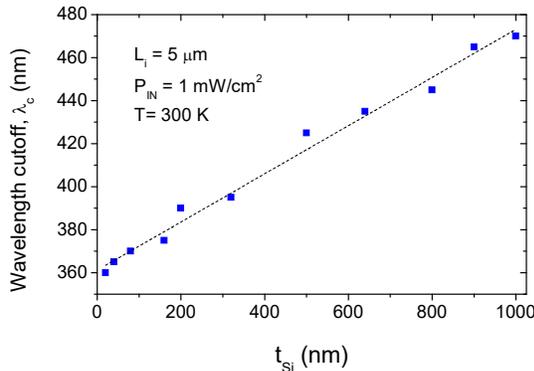

Fig. 13 Wavelength cutoff as a function of silicon film thickness.

The responsivity and total quantum efficiency as a function of silicon film thickness are shown in Figure 15. It can be noted that the responsivity varies between 62 mA/W, achieved at shorter wavelengths, and 80 mA/W at longer wavelengths, showing that there is a contribution to the increase in responsivity with the increase on the silicon film thickness. The maximum quantum efficiency reached for a device with L_i = 5 µm is around 21%, for UV wavelengths and thin silicon film thicknesses the maximum efficiency is reached in the first 100 nm of silicon. For wavelength of 470 nm, the same is not yet observed for t_{Si} up to 1 µm.
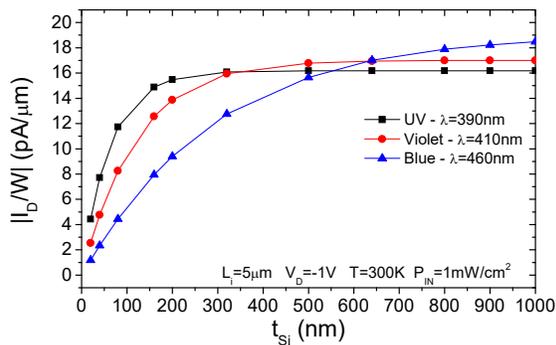

Fig. 14. Normalized absolute total current, $|I_D/W|$ under UV, violet and blue illumination, as a function of silicon film thickness.

IV. CONCLUSIONS

In this work lateral PIN SOI photodiodes were studied by means of experimental data and numerical simulations. The experimental results of responsivity from 73 to 98 mA/W and quantum efficiency from 23 to 33% presented in this work are considered satisfactory when compared with the results found in the literature. Photodiodes with similar characteristics had responsivity between 70 and 100 mA/W in [4] and quantum efficiency between 45% and 60% in [7].

Temperature, intrinsic region length and silicon film thickness were varied. It has been shown that temperature change does not affect the absorption of light. On the other hand, longer intrinsic lengths increase the photosensitive area, raising the photocurrent. However, long intrinsic lengths also favor recombination, reducing the current. While the intrinsic length does not change absorption, the increase of silicon thickness allows for longer wavelengths to be absorbed. A linear relation between the wavelength cutoff and

silicon thickness has been observed, which can help defining the best technology for detection of a given wavelength. The presented results indicate that geometrical and technological parameters can be properly chosen depending on the application.
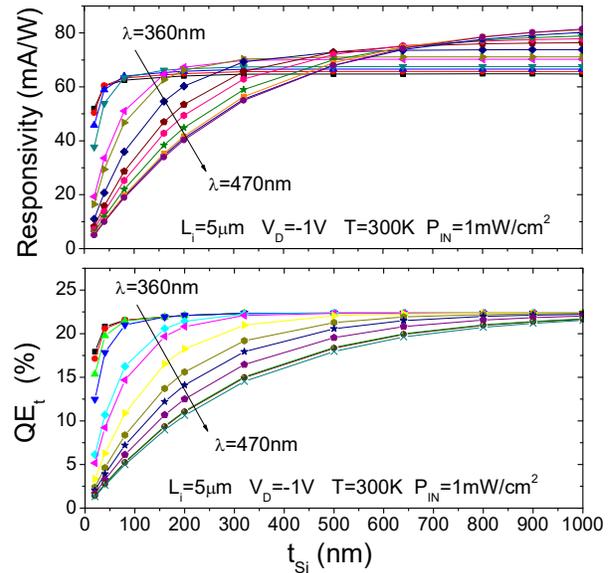

Fig.15 Responsivity and total quantum efficiency under UV, violet and blue illumination as a function of silicon film thickness.

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