

Waveguide-detector system on silicon for sensor application

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Abstract

A whole silicon monolithic waveguide-detector system is studied. Four different coupling electrophotonic devices are presented. One of them is analyzed in detail. The studied system consists of a planar p-n junction with a waveguide built in a cavity in front of it. The output port of the waveguide faces directly to the depleted layer maximizing absorbance of all photons. The waveguide is experimentally fabricated and characterized, and light on the visible range is transmitted in multimode. The simulation of the fabrication process considers an N-type silicon substrate, whose resistivity is varied from $10 \Omega \times \text{cm}$ to $1000 \Omega \times \text{cm}$. The diode sensor is characterized by computational simulation, and the model is validated using characteristics of diodes previously fabricated. The dark current, the electric field and the characteristics of the depleted zone are obtained to optimize the design of the system. Electrical stimulations are performed for bias voltages of 0 V, -5 V, -10 V, -20 V and -30 V. The simulation results show that the proposed coupling scheme enhances the generation of photocurrent, which results from all the photons emerging from the waveguide and impinging directly on the space charge region. Copyright © 2018 VBRI Press.

Keywords: Silicon photonics, waveguide, detector, electrophotonic system

Introduction

It is well known that silicon integrated circuits have grown following Moore's law, and currently integration rates go beyond the billions of transistors per chip. However, not only the miniaturization has a physical limitation, but power dissipation management, the requirement of high data rates, and many other, are significant problems to be solved as integration goes further, making it increasingly difficult to comply with Moore's predictions.

In order to overcome the aforementioned issues, many approaches have been proposed, such as the integration of three dimensional devices, or wafer stacking [1], [2]. However, in spite that such approaches help to increase the density of integration, the physical limitations intrinsic to silicon electronics are not solved yet.

There is a consensus that in order to really surmount the limits that make impossible the continued increase of the integration in silicon circuits, the use of photons instead or along with electrons is the most promising solution [3]. Therefore, different lines of research have been proposed to obtain photonic integrated circuits. The main idea is to take advantage of the established techniques used to obtain electronic integrated circuits

(ICs), especially if all silicon ICs are considered. Planar IC technology has been used to develop the so called integrated optics. These are photonic systems integrated on a monolithic substrate based on light wave circuits. When these systems include only optical systems, they are called integrated optic circuits. A present endeavor of optical circuits is the development of quantum computers and quantum communications [4], [5], [6].

However, there is another approach, which includes the use of both electrons and photons. These systems are called electrophotonic systems [7]. The range of practical applications for electrophotonic is quite wide, ranging from the massive transference of data between silicon chips, to the detection of pollution, passing through the characterization of biological specimens. Due to the significant number of circuits required for such applications, and because of the relatively low costs of fabrication, it is mandatory for these circuits to be compatible with the standard Silicon IC technology in general, the most widely used is the CMOS technology. For this reason, the described scheme is called all silicon integrated optoelectronics, or electrophotonics. Despite its many advantages, electrophotonics presents several limitations to overcome. Perhaps the most challenging device to be fabricated in all silicon electrophotonic integrated circuits is the light source, since silicon is a

poor light emitting element due to its indirect bandgap nature. To overcome this limitation, the use of mixed technologies is the usual approach. For instance, external lasers or heterogeneously bonded light sources are used to produce the light required for the optical devices. Certainly, this involves technological complications, such as high losses, higher costs, and many other significant disadvantages.

An example of a mixed technology is reported in [8], where a microprocessor and a bank of static random-access memory are communicated using light. In this work, all the optical devices, except for the light source, are built inside the chip. Silicon biosensors with sensing and diagnosis capabilities than cannot be obtained using only photons, can be achieved using electrons and photons in the same chip [9]. An example of this is the work developed by Lechuga et al., who have developed integrated interferometric silicon bio-sensing systems capable of detecting environmental pollutants in concentrations down to 0.1 ng/ml [10]. However, their system also must use an external diode laser due to the lack of an integrated silicon light source, and this is a setback in the achievement of a real full lab-on-a-chip scheme. To fulfill an all silicon electrophotonic system, three silicon compatible basic elements are necessary: a light source, a waveguide, and a light sensor. As implied before, the silicon light source is the most difficult to obtain, and researchers have been studying light emitting silicon compatible materials for many years. One of these is the off-stoichiometry silicon oxide, also known as Silicon Rich Oxide (SRO). The SRO obtained by Low Pressure Chemical Vapor Deposition (LPCVD) is simple to fabricate, and has high emission properties [11]. Light emitting capacitors using SRO as active material have a wide emission spectrum response, from 400 nm to 850 nm. However, the light intensity obtained from these devices is not comparable to that from a laser [12]. Nevertheless, aside from its integrability, a significant advantage of this material is the simple way to change its electrical and optical properties through the modification of the silicon excess, which on its turn is controlled through the modification of the ratio of reactive gases (R_0) during the deposition, defined as $R_0 = P[N_2O]/P[SiH_4]$ where $P[N_2O]$ and $P[SiH_4]$ are the partial pressures of Nitrous Oxide and Silane, respectively [11]. SRO-based Light Emitting Capacitors (LECs) can be used as an integrated silicon-based light source, obtaining the most difficult of the three required elements. Regarding the remaining two, namely the silicon compatible waveguide and photodetector, the first one can be obtained using silicon nitride, also fabricated by LPCVD; and the light detector can be as simple as a p-n silicon Junction. However, due to the relatively low intensities provided by a LEC [12], it is necessary to propose innovative photo-sensing devices and concepts that can detect very small signals.

In this work, we propose a topology of a waveguide-sensor pair that can be only conceived as electrophotonic systems. The waveguide and the sensor are designed considering the wavelengths emitted from the LEC.

Details of the design, simulation, and experimental characterization of the waveguide are presented. Computer simulations of the sensor are also shown. Currently, the experimental waveguide-sensor pair is under fabrication.

High sensitivity light detector concepts

One of the most important advantages when integrating the light source, the waveguide, and the detector in the same piece of silicon, is that the elements are self-aligned. An example of such system was reported in [13, 14]. In [14], the same slab of silicon nitride is common to the light emitter, the waveguide and the sensor. Thus, the whole system can be classified as a single electrophotonic device. The light emitter uses a combination of SRO and Silicon Rich Nitride (SRN) as the active material, and the silicon excess in both is obtained simultaneously by Silicon implantation. The silicon nitride film forming the emitter is continued to become the waveguide, and it finishes on a p-n junction. In this case, the diode detects the evanescent field of the transmitted light. The fact that the three elements share a common material prevents injection and coupling losses, allowing for the transmission and further detection of the relatively low emitted signal. The proposal is to design the electrophotonic devices with materials routinely employed in microelectronics technologies, but thinking and using them in innovative ways. In **Fig. 1**, four electrophotonic systems are proposed. The main advantage of two of them is that the relatively weak signals transmitted by the waveguides are amplified by the detector itself (a and b), and the third one (represented in c) intends to avoid the signal passing through a highly doped layer, and instead falling directly upon the Space Charge Region (SCR), where most of the photogenerated electron-hole pairs can be used. The scheme depicted in **Fig. 1(d)** has already been fabricated and tested as reported in [14], and it is included in this work as the device of reference according to the state of the art. A fifth option would be the combination of the schemes depicted in (c) and (d), i.e. use a horizontal diode with the SCR directly under the waveguide to detect the evanescent field, while avoiding the pass of the photons across a highly doped region.

Fig. 1(a) shows the schematic of an electrophotonic device composed by a waveguide and a Metal-Insulator-Semiconductor (MIS) transistor where the same silicon nitride used to guide the light plays the role of the oxide in a regular MOS transistor. The evanescent field will generate electron-hole pairs in the channel and the depletion layer, therefore modulating the amplification through the signal arriving to the gate (waveguide). The detector can also work on weak inversion, or even with the surface depleted, depending on the bias applied to the gate terminal. **Fig.1(b)** is a variation of the scheme depicted in **Fig.1(a)**. In this case, a bipolar transistor is used instead of a MIS structure. As can be seen, the waveguide ends on the base of the transistor. Therefore, the current gain for the structure based on a bipolar

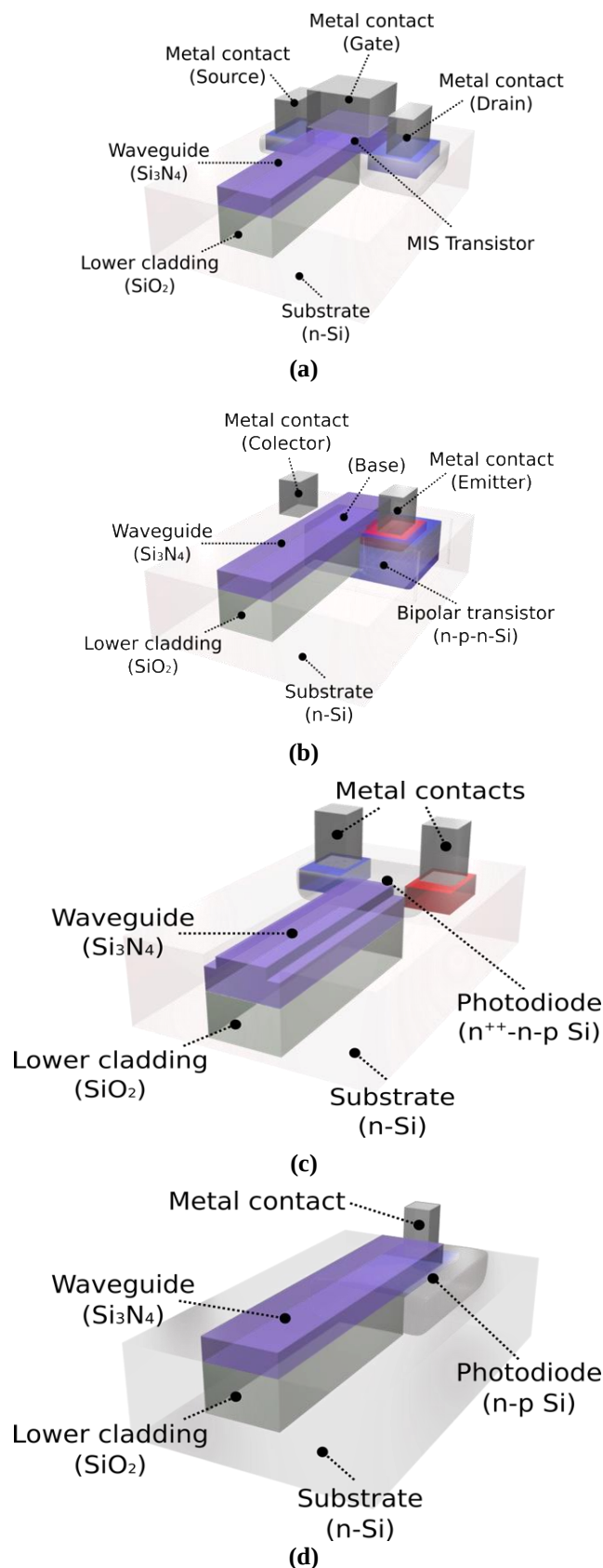


Fig. 1. Waveguide-sensor pairs designed to improve the detection of weak signals. (a) The gate of a MIS transistor is built using the same silicon nitride that conforms the waveguide. (b) The waveguide finishes on the base of a bipolar transistor. (c) The waveguide ends just in front or on the depletion layer of the p-n junction. (d) The same concept as that in (c), but the waveguide ends on a lateral p-n junction.

transistor can be much higher than that of a MIS. In addition, this structure does not require metal to be deposited on the silicon nitride, allowing for different materials to be used on top, such as light sensible materials to improve the detection. As well as in the previous concept, the control of the amplification, normally performed by an electrical signal in the base, will be produced by the optical signal transmitted through the waveguide, allowing for large changes in the signal detected at the collector with small optical signals arriving at the base.

Fig.1(c) illustrates a different concept. In this case, a planar p-n junction is used in such a way that the light coming out of the waveguide impinges directly on the SCR of the diode. The waveguide is built in a cavity in front of the sensor, allowing for all the photons that arrive to the wall of the sensor (and create electron-hole pairs) to be separated and hence contribute to the photocurrent. Finally, for the case of the topology shown in **Fig.1(d)**, the waveguide and the diode are built on the same surface, therefore the evanescent field from the waveguide is the signal to be detected across diode's anode. The latter is the simplest scheme, and as mentioned, it has been already tested [14]; however, optimization is still required.

Despite of the novelty and potential of all schemes here presented, in this work we analyze the electrophotonic system shown in **Fig.1(c)**, and contrast it with the topology presented in **Fig. 1(d)**, setting aside deeper analyses of the schemes proposed in **Fig. 1(a)** and **1(b)** for further publications. The proposed waveguide for the scheme depicted in **Fig. 1 (c)** was fabricated and experimentally characterized, while the sensor has only been computationally simulated.

Waveguide

Fabrication

The processes started either growing or depositing, 2 μm of SiO_2 on a P type silicon wafers (100). This film is the bottom cladding of the waveguide. In this work, we report results of samples with 2 μm thick SiO_2 claddings obtained by either thermal oxidation of the wafer, or by Chemical Vapor Deposition.

After this, SRN films of a nominal thickness of 450 nm were deposited by LPCVD using SiH_4 and NH_3 as precursor gases. Similarly to the SRO, the ratio of the partial pressure caused by the flow of the precursor gases used during the SRN fabrication is defined as $R_N = P[\text{NH}_3]/P[\text{SiH}_4]$. In this experiment two different silicon contents were used corresponding to $R_N=100$, and $R_N=120$. As R_N increases, the Si excess augments [15]. The geometry of the waveguides was then defined by lithography and Reactive Ion Etching of the SRN films, producing waveguide widths of 5 μm , 10 μm and 15 μm . Finally, the samples were submitted to a thermal treatment for 120 min at 1100 $^\circ\text{C}$ in N_2 atmosphere, in order to replicate the conditions to which they would be subjected in a process that would integrate light sources based on SRO [13].

Characterization

An image of the cross-section of the waveguide obtained by Scanning Electron Microscopy (SEM) is presented in **Fig. 2**. It shows the waveguide composed by a 0.5 μm -thick SRN film, a bottom cladding with a 2 μm thickness, and the silicon substrate used as mechanical support.

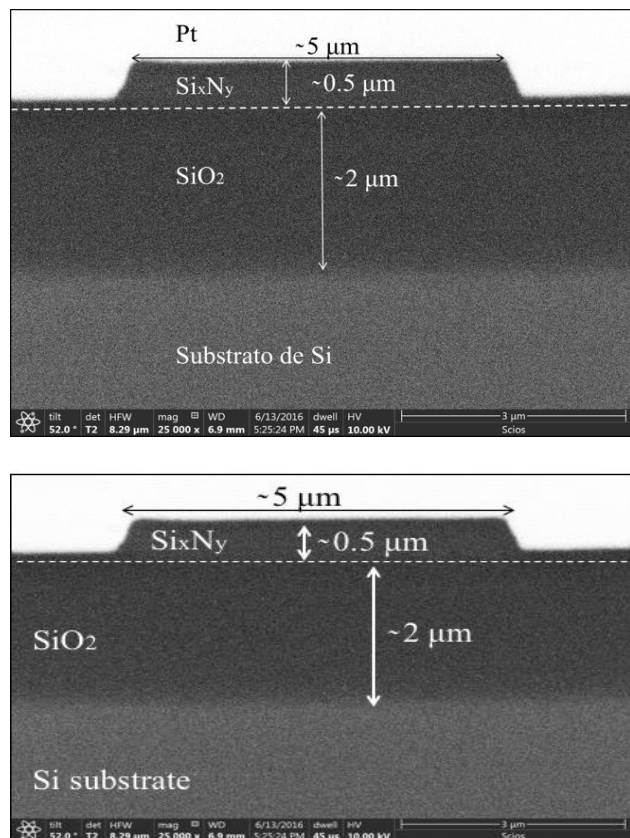


Fig. 2. SEM image of the cross-section of a waveguide fabricated using $R_N = 100$. The contrast between gray scales indicates the different materials.

A free space configuration as the depicted in **Fig. 3** was used to characterize the field distributions of the fabricated waveguides. Two light sources were used: an OEM diode laser model LSR473NL-80 with 70 mW of optical power and $\lambda_b = 473$ nm (blue), and a He-Ne JDS Uniphase laser model 1125 with an optical power of 5 mW and $\lambda_r = 633$ nm (red). The output of the waveguide was monitored using a CCD BC106-VIS Thorlabs beam analyzer with a detection range from 350 nm to 1100 nm.

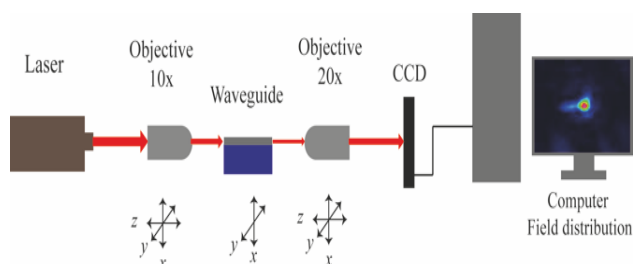


Fig. 3. Setup to measure the field distribution, in a free space configuration, of the output port of the optical waveguides.

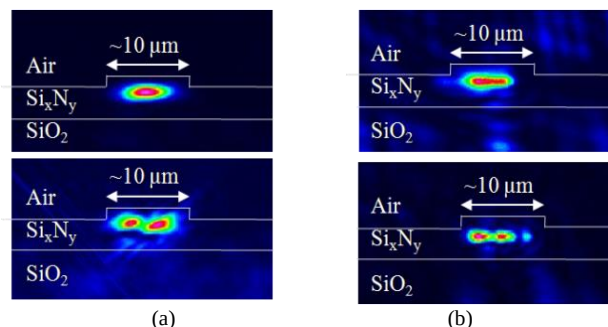


Fig. 4. Field distributions for a rib optical waveguide 10 μm -wide and $R_N = 100$. (a) Energy distribution for TE_{00} (top) and TE_{10} (bottom) modes with $\lambda_b = 473$ nm. (b) Energy distribution for TE_{00} (top) and TE_{20} (bottom) modes with $\lambda_r = 633$ nm. White lines are used with illustrative purpose and they are not to scale.

Fig. 4 shows the field distribution for a 10 μm -width rib waveguides using either blue or red light. As it can be observed, the waveguides are able to transmit both wavelengths, with multimodal operation. This is an important result, since the SRO-based LECs exhibit a wide electroluminescence spectrum (400 nm to 850 nm). However, LECs also present a low optical power (in the order of μW), as well as a broad range of wavelengths that can propagate. Another aspect is the field distribution, which is confined under the rib, and depending on the propagation mode, the maximum energy is located at 1/2, 1/4 or 3/4 of the rib width.

Photodetector

Simulations details

The software SILVACO was used to simulate the fabrication process (Athenas module) and electrical stimulation (Atlas module) of the sensor showed in **Fig. 1 (c)**. For the simulation of the fabrication, an N-type (100) oriented silicon substrate was used. Based on the available wafers for a further fabrication, the resistivity of the substrate was varied from 10 $\Omega \times \text{cm}$ to 1000 $\Omega \times \text{cm}$, in order to evaluate the Lateral Width of the Space Charge Region (LW-SCR) as a function of applied voltage. The P-doped and N+-doped regions were respectively simulated by thermal diffusion of Boron and Phosphorous at 1000 $^{\circ}\text{C}$, with drive-in times of 120 min and 30 min, respectively, both at 1100 $^{\circ}\text{C}$. A separation of 20 μm between P and N+ regions was considered. This length takes into account the dimensions of the waveguide (10 μm of width) and the overlap between different masks. Finally, the contacts to the P and N+ regions were simulated to be made of Aluminum. **Fig. 5** shows a cross-section of the simulated planar diode, and the waveguide output port. The junction depth is labelled " x_j ". The electrical stimulation was performed biasing the diode with 0 V, -5 V, -10 V, -20 V and -30 V. At each voltage, the LW-SCR, the current density, and the electric field were analyzed. It is important to assure that the electric field in front of the waveguide is oriented in such a way that all the photons arriving will contribute to the photocurrent.

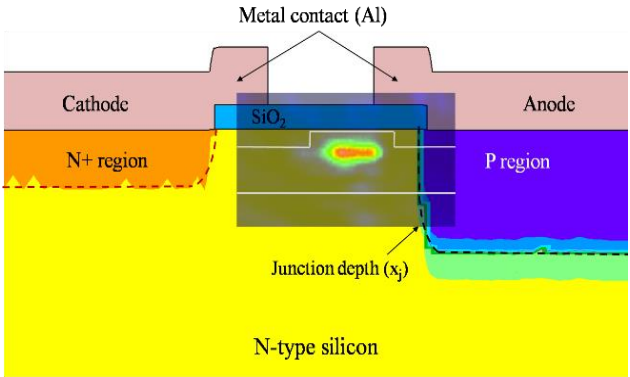
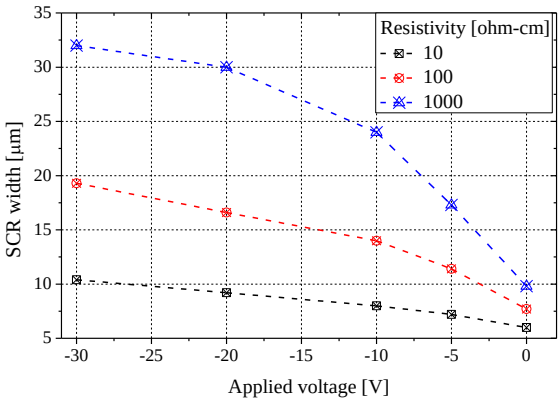


Fig. 5. 2D image of the simulated sensor, schematic of the waveguide output and the electric field transmitted, as shown the photons arriving to the p-n junction impinge on the SRC region. A separation of 20 μm is used between contacts (anode and cathode) to provide enough space to the zone where the waveguide is located. As it can be observed, light emerging from the waveguide will be absorbed directly in the space charge region.

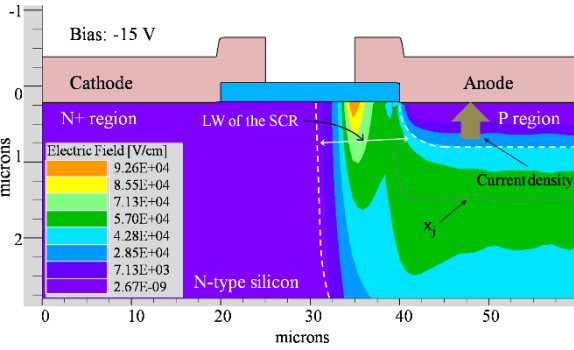
Computational results of the sensor

Fig. 6(a) shows the SCR width as a function of the substrate resistivity and the applied voltage to the diode. As it can be seen, a resistivity higher than 100 $\Omega \times \text{cm}$ and a low voltage (around -5 V) allow for SCR widths greater than 10 μm , which is enough to cover the output port of the waveguide.

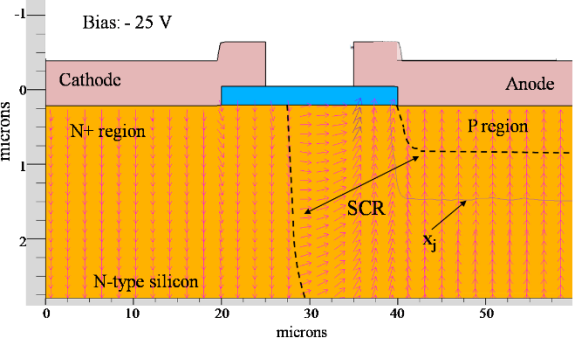
Fig. 6(b) depicts the magnitude of the electric field inside the SCR under a bias of -15 V, and a 10 $\Omega \times \text{cm}$ substrate resistivity. The color scale indicates the electric field magnitude in V/cm. The orange zones represent an electric field of 92.6 KV/cm, whereas the purple zones represent an electric field close to 0 V/cm. The LW-SCR is indicated with a white line, and a gray arrow indicates the zone where the dark current density was evaluated. In order to take the most advantage of the arriving photons, the LW-SCR is the region where the waveguide must be located. As it can be observed, the substrate and bias should be chosen in such a way that the resulting LW-SCR is greater than 10 μm , allowing for some aligning mismatching. **Table 1** summarizes the values of the junction depth, the LW-SCR, and the dark current density, as obtained when the substrate resistivity and the electrical polarization are varied during the simulation. The dark current is in all cases in the order of 10^{-9} A/cm².



(a)



(b)



(c)

Fig. 6. (a) Plot of the SCR width as a function of substrate resistivity and applied voltage to the diode. (b) Results of magnitude (color scale) of the electric field in the simulated planar sensor, under a bias of -15 V. A gray arrow indicates the zone where dark current density was evaluated. (c) Image that illustrates the electric field direction (arrows) of a diode fabricated on 10 $\Omega \times \text{cm}$ resistivity substrate and biased under -25 V.

Table 1. Results of junction depth (X_j), Lateral Width of the Space Charge Region (LW-SCR) and Dark Current Density (J_{dark}) for different substrate resistivity and electrical polarizations of the sensor.

ρ [$\Omega \times \text{cm}$]	X_j [μm]		Voltage [V]				
			0	-5	-10	-20	-30
10	1.15	LW-SCR [μm]	6.0	7.2	8.0	9.2	10.4
		J_{dark} [A/cm ²]	0	3.0E-09	3.8E-09	6.6E-09	1.2E-08
100	1.52	LW-SCR [μm]	7.7	11.4	14.0	16.6	19.3
		J_{dark} [A/cm ²]	0	1.8E-09	1.9E-09	2.0E-09	2.2E-09
1000	1.81	LW-SCR [μm]	9.8	17.3	24.1	30.0	32.0
		J_{dark} [A/cm ²]	0	1.75E-09	1.77E-09	1.80E-09	1.85E-09

Fig. 6(c) illustrates the electric field direction inside the SCR. It is evident that the electric field will drive the photogenerated electrons and holes towards the anode and cathode, respectively. In this case, the diode was simulated considering a substrate resistivity of $10 \Omega \times \text{cm}$ and a voltage of -25 V . These are the conditions to assure that the output port of a $10 \mu\text{m}$ -width waveguide is covered by the SCR. If a lower substrate resistivity is used, then higher voltages are required to produce an SCR wide enough to contain the whole waveguide output port. Another option is to use a higher resistivity substrate, since low voltages will be then needed to bias the diode to produce a depletion layer of $10 \mu\text{m}$ or more.

Considering the fundamental mode (TE_{00}) transmitted by the waveguide, the highest density of energy falls on the middle of the depleted zone, avoiding border effects of the SRC and assuring generation of photocurrent.

As it was previously mentioned, the waveguide will be fabricated in front of a lateral wall of the sensor, and the simplest position is the suggested in Fig. 5 because it only needs one geometrical parameter to be aligned. However, as shown in **Fig. 6(b)** and **6(c)**, the electric field is oriented towards the silicon-oxide interface, reaching a maximum point directly below the beginning of the anode metal contact, anticipating carrier charge accumulation, which may reduce the photocurrent generation efficiency. To solve this problem, two options are considered. The first one is to design a layout in which the metallic anode contact does not surpass the LW-SCR. The second one is to locate the waveguide in the zone under the P+ region, to allow for a more efficient trajectory of the generated e-h pairs towards the terminals of the diode. As it can be seen in the **Fig. 6(c)**, in this region the electric field is straight toward the P+ diffusion. However, the latter solution involves some technological difficulties, as the fabricated cavity to place the waveguide must be deeper, and the aligning of the waveguide and the sensor will depend on the junction depth and not only on the geometry of the devices.

In [14] an electrophotonic system was reported, which integrates a light source, a waveguide and a sensor, all in silicon. To compare and confirm that the sensor proposed here is a step forward towards performance enhancement of the existing sensors, the diode reported in [14] was also simulated. This diode has been already fabricated and electro-optically tested, showing enough sensitivity to detect the emitted and transmitted light from the LEC. As mentioned, such sensor detects the evanescent light coming from the waveguide. The experimental results of the reported diode showed that diodes with 1 mm^2 areas have an average dark current density of $50 \times 10^{-8} \text{ A/cm}^2$ [16], while the simulation results showed $1 \times 10^{-8} \text{ A/cm}^2$, validating our simulation model within an order of magnitude. Thus, it is expected for our experimental results after fabricating the sensor here proposed to agree with those from simulation.

As it is well known, I_{ph} is obtained as:

$$I_{ph} = I_{IL} - I_d \quad (1)$$

where I_{IL} and I_d are, respectively, the currents under illumination and dark conditions. Considering the results of simulation, the dark current in the diode here proposed will be lower than that reported in [15], meaning that at least a similar sensitivity is expected.

The I_{IL} depends on two factors: the optical power of the light source and the wavelengths that the diode can detect. In this regard, the diodes of the electrophotonic system must sense light from SRO-based light sources, with irradiance on the order of $\mu\text{W/cm}^2$ [12]. Thus, one option to improve the I_{IL} is to produce more efficient silicon light sources, which are independent of the sensors. However, the second option is to capture as much light of as many of the emitted wavelengths as possible. This latter approach does directly depend on the design of the diode. For example, the diode reported in [14] detects light through evanescent field and is not able to generate I_{ph} of wavelengths between 400 nm and 670 nm , because they are absorbed in a high-doped layer and outside of the SRC, meaning that the electron-hole pairs generated do not contribute to the photocurrent.

However, the fact that the light impinging in our structure is not evanescent, and it will directly impinge on the SRC (and not pass through a high-doped layer) assures that a better result will be achieved. So, the proposed waveguide-diode pair will produce higher values of I_{ph} with respect to the diode reported in [14]. This is an important improvement of the electrophotonic system that points to achieve a more efficient all-silicon photonic integrated circuits, which could test biomolecules in a low concentration or used for Lab-on-a-chip applications in general.

Conclusion

Four different electrophotonic devices coupling the waveguide and the sensor were proposed. One of them that locates the waveguide in front of the lateral wall of the sensor was analyzed in detail. The studied device uses a rib waveguide built into a cavity and a planar p-n junction, in such a way that the light emerging from the waveguide impinges directly on the space charge region of the sensor. The waveguides were built and characterized. Experimental results showed that light in the visible range was transmitted, and multimodal transmission was obtained. The sensor was computationally simulated. Based on computational simulations, the best results were achieved when substrates with resistivity of $100 \Omega \times \text{cm}$ or higher for the diode fabrication were used and the detector was biased with low voltages (around -5 V). These conditions are enough to assure that SCR covers the output port of the waveguide and the photogenerated current will be improved. If substrates with higher resistivity are used, then even lower diode biasing voltages are required, hence reducing the dark current and enhancing the sensor sensitivity. Our simulation models were validated by a match with experimental results from diodes previously reported in [13]. The efficiency of our sensor is expected

to improve as compared to the one reported in [13], since unlike the case of the latter, in the one here proposed the whole beam from the waveguide output port will impinge on the SCR of the sensor. Finally, as the theoretical studies predict proper functioning of the waveguide-sensor pair, the complete experimental integrated electrophotonic system is currently under fabrication.

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Author's contributions

All the authors form a team that contributes continually to the development of all of our experiments, analyze results, advise graduate thesis, and leads students to obtain good conclusions. Thus, it is difficult to assign precise tasks to each one. However, specifically for this paper: JAS designed and fabricated waveguide samples, as well as simulated the electrophotonic systems. GVV characterized the waveguides. AAGE, JPC, IEZH and MAM conducted the discussion of the results and wrote the paper. Authors have no competing financial interests.

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