Plasmonic Enhanced Photodetectors for Near Infra-red Light Detection (PlaSiPM)

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ABSTRACT

In recent years there has been a growing demanding of optical sensors able to detect near-infra-red photons with single-photon resolution, high quantum efficiency (> 20%) and ultra-fast time resolution (10-50 ps). In the PlaSiPM project, we demonstrated that the integration of plasmonic nanostructures on silicon photomultipliers is a promising solution to cope with these requirements. We experimentally demonstrated a quantum efficiency enhancement of 45% at 950 nm with respect to a standard reference sample, and numerical simulations suggested new optimizations leading to an eight-fold increase of quantum efficiency at that wavelength. These results are going to be effectively exploited in several emerging applications with a high social impact, from autonomous driving to biosensors.

Keywords: SPAD; SiPM; surface plasmon polaritons; Si photodetector; plasmonic.

1. INTRODUCTION

Silicon based single photon avalanche diodes (SPAD) are already a valuable technological solution to detect and accurately measure photons in the visible spectrum (400 nm – 600 nm). Arranged in extended arrays as Silicon PhotoMultipliers (SiPM), they can provide both single-photon counting sensitivity and fast time resolution in large-area detectors. Nowadays, new emerging applications require sensors with ultra-fast time resolution and high efficiency for the detection of photons in the near-infra-red (NIR) region of the spectrum (800 nm – 1000 nm). Some of these applications are: light detection and ranging (LiDAR); time-of-flight imaging; biosensors; quantum computation, readout of NIR emitting scintillator crystals. All these applications are now still hampered by the limited availability of optical sensors with the desired performance.

In this paper we propose a new concept of SPAD and SiPM detectors integrating plasmonic nanostructures, provided with high photon-detection efficiency (PDE) in the NIR spectral range and preserving at the same time all the advantages of the standard SiPM technology. The main breakthrough aspects of the proposed devices are:

- High PDE in the NIR spectral range (>40% at 900 nm and >20% at 950 nm);
- High single-photon time-resolution;
- High dynamic range due to the small SPAD size (lower than 10 µm);
- low production costs, thanks to the compatibility with standard CMOS fabrication process.

The feasibility of the proposed scheme has been experimentally demonstrated by the production of test samples of silicon photodiodes integrated with metal (silver) nanograting structures supporting Surface Plasmon Polaritons (SPP). The nanostructures are fabricated directly on the top of the photodiodes by Electron Beam Lithography (EBL) followed by silver evaporation and lift-off. The metal nanograting has been designed to support hybrid opto-plasmonic modes that confine the light in the sensing volume of the sensor, thus enhancing the absorption of NIR photons. The quantum efficiency (QE) of the first prototype is improved up to 45% at 950 nm with respect to a reference naked photodiode (PD). In addition, numerical simulations suggest that an optimized metallic nanograting could reach an improvement up to 8 folds at 950 nm with respect to the reference, paving the way to the realization of a high-efficiency NIR SiPM.

2. STATE OF THE ART

SPADs and SiPMs are typically based on thin silicon epitaxial substrates (just 3-5 µm thick), which allow to reach both high PDE in the UV/visible part of the spectrum and low time jitter (down to tens of ps). For instance, the SiPM technology developed at Fondazione Bruno Kessler (FBK) features PDE approaching the 60% at 420 nm and single-photon time resolution of about 50 ps [1]. Commercial products with similar performance are also available by other manufacturers. On the other hand, the PDE of standard SiPMs is strongly limited in the NIR spectral range due to the relatively low Si absorption coefficient [2]. The latter implies absorption depths much larger than the active thickness of the sensor, i.e. few micrometres for the latter against ~18 µm absorption depth at 850 nm and ~150 µm at 1000 nm. Therefore, the typical PDE of SiPM at 900 nm and 950 nm is only 10% and 5%, respectively, which is considered low for most of the previously cited applications.

A possible technological solution to overcome this limit is the using of a thicker substrate, which allows to extend the avalanche region or the depletion region through a thicker silicon portion. As an example, a SiPM based on thick epitaxial layers and featuring a moderate improved efficiency up to 7% at 950 nm, has been recently demonstrated at FBK [2]. However, these solutions typically come with a deterioration in time jitter, optical cross-talk (CT) and put a limit in the single SPAD lateral dimension. Time jitter is degraded due to the slower drift/diffusion process in the thicker substrate, while optical CT (originated by photons emitted during the avalanche and re-absorbed by the neighbouring cells of the SiPMs) is increased due to the higher active thickness. In addition, the minimum achievable SPAD lateral size is limited by the cell aspect ratio (lateral-to-thickness ratio), as some issues due to electric field non-uniformities are introduced when the aspect ratio becomes lower than 10 [2].

3. BREAKTHROUGH CHARACTER OF THE PROJECT

Latest developments in nanophotonics and plasmonics showed that nanostructures supporting SPPs could be effectively used to enhance the absorption of NIR photons in thin poor-absorbing materials like silicon. Several studies have been carried out on the coupling of photonic structures on solar cells or photodetectors [3], but no attempts have been carried out with single-photon silicon detectors.

The new device concept proposed in this work is based on thin (3 µm) silicon detector coupled with metal nanostructures that are directly integrated on the sensor at the back end of line. The proposed device has the potential to break the current trade-off between jitter, PDE, and correlated noise. A PDE above 20% at 950 nm is realistic, as suggested by optical simulations; while time jitter and optical CT are preserved thanks to the limited active thickness. In addition, these devices preserve all the advantages of the silicon-based IC technology and thus the potentiality to be implemented on an industrial scale.

The most innovative part of the PlaSiPM approach consists in the direct integration, in the same chip, of a CMOS component (the SiPM) with a photonic one (the plasmonic grating) which result in a new device with additional functionalities.

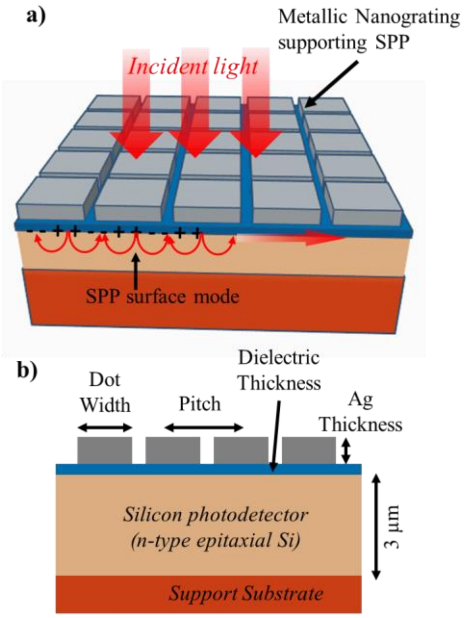

Figure 1. Proposed structure of metal nanograting fabricated on the top of a silicon photodiode passivated with a thin dielectric film (a); cross section of the same structure where the parameters optimized in the simulations are indicated (b).

4. PROJECT RESULTS

The proposed detector structure is presented in Fig.1, where not-in-scale 3D sketch (a) and cross-section (b) of the device are shown. In this design, the silicon photodiode consists of a thin silicon slab (3 µm thick), which is the typical thickness used for SiPMs and SPAD production. The top detector surface is covered by a thin dielectric film (silicon nitride) that passivates the detector surface and reduces the surface recombination velocity. The thin dielectric layer acts also as an optical coupling layer between the detector and the plasmonic nanograting and requires a fine tuning of its thickness. The nanograting supporting SPP modes consists of an array of squares, and it is being fabricated directly on the top of the detector in order to lie very close to the active part of the sensor. In order to finely tune the detector design and estimate the nanograting optical performance, finite-difference time-domain simulations were undertaken, by using a commercial simulation engine (FDTD Lumerical [4]). With reference to Fig.1b, all the represented geometrical parameters of the structure have been tuned with the aim of maximizing the absorbed power fraction in the silicon substrate at 950 nm. The most promising structure features a pitch of 530 nm, duty cycle of 80% (defined as the ratio between square width and pitch), 100 nm thick Ag and a <15 nm thick Si_3N_4 film. The absorbed power fraction as a function of wavelength with this set of parameters is represented in Fig. 2a (orange solid line) together with the absorption curve of 3 µm thick Silicon without Ag grating (blue solid line), used as reference.

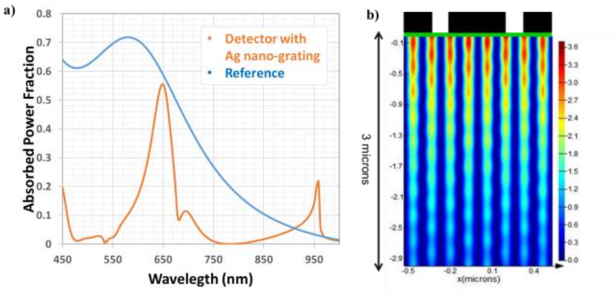

Figure 2. a) Simulated absorption in the 3 µm thick silicon detector with Ag nano-grating (orange solid line) and without (blue solid line); b) absorbed power density in the detector cross-section (a.u) at 952 nm.

The simulated spectrum shows multiple absorption peaks that can be related to both plasmonic and hybrid opto-plasmonic resonances. In particular, at 950 nm, a narrow and asymmetrical "Fano-like" absorption peak is present, in correspondence of the Rayleigh singularity wavelength [5]. At that wavelength the absorption reaches the 25%, an eight-fold enhancement with respect to the reference. The physical interpretation of these resonance peaks goes beyond the scope of this paper and can be found in [6]. The map of the absorbed power density at 952 nm, corresponding to maximum of that absorption peak, is reported in Fig. 2b, where it is clearly visible the light confinement in the first micron due to excitation of the hybrid opto-plasmonic mode.

The integration of Ag nanosquares in direct contact with the detector surface poses new challenges in both the micro- and nano-fabrication process that have to be compatible with each other.

The manufacturing technology and the layout of the photodiode have been specifically designed to host the nanostructure. The most critical parameter of the new diode design is the ultra-thin (<15 nm) dielectric passivation layer, required in between the nanograting and the Silicon. Small square diodes with different lateral dimensions (100 - 500 µm) were produced on a (3.5 ± 0.5) µm thick n-type epitaxial-Silicon wafers, using a CMOS-like manufacturing technology similar to the one used in the FBK Near Ultra Violet, high-density (NUV-HD) SiPM [1].

To integrate the metallic nanograting directly on the sensor surface, we developed and optimized a process based on positive-tone resist patterning by means of Electron Beam Lithography (EBL), ultra-high vacuum metal evaporation and lift-off. EBL provides adequate lateral nanometric resolution without introducing any defects or damages to the sensor. The optimization of the EBL process has required a lot of effort to achieve a good accuracy in the final dimensions of the squares of the arrays. Ag evaporation was carried out in an e-beam evaporator, without an adhesion layer to preserve the plasmonic properties of the structures. The resulting Ag grating is reported in fig. 3.

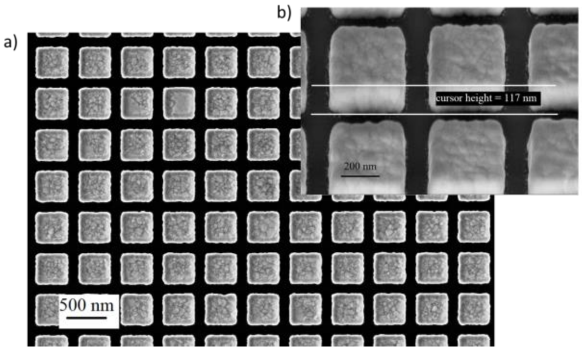

Figure 3. SEM planview of a nanosquare array produced on the surface of a PD. Design square size is 400x400 nm with 535 nm period, Ag thickness is 117 nm.

The electro-optical characterization is carried out by using a custom setup composed of: a broadband halogen and unpolarized lamp; a monochromator with ~1 nm spectral resolution; a calibrated reference diode that measure the incident power; a semiconductor analyzer connected to the device under testing. Two PD samples with different array geometry have been characterized together with a reference diode (without nano-grating) fabricated on the same silicon chip. The two samples differ in terms of grating duty cycle and Si_3N_4 layer thickness, as shown in the following table, which reports the nominal values of the main geometrical parameters of the samples.

Sample ID	W509	W609	Reference
Grating pitch	535 nm	536 nm	-
Duty cycle	76%	66%	-
Si_3N_4 *Thickness*	11 nm	6.6 nm	11 nm
Ag Thickness	115 nm	115 nm	-

The experimental QE of both the PDs provided with squares-arrays (black and orange solid lines for W5.09 and W6.09, respectively) together with the reference diode (blue solid line) are reported in Fig. 4, while the ratio between the QE of the two PDs with squares-arrays and the QE of the reference diode are reported in Fig. 5. It is

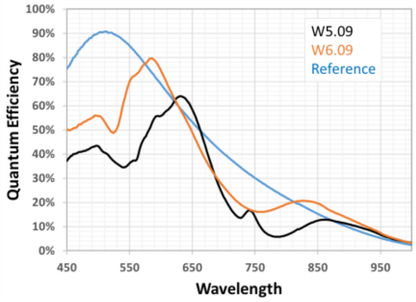

Figure 4. QE as a function of wavelentgh of the two PD with nanogratings (orange and black lines) and of the reference PD without nanograting (blue line).

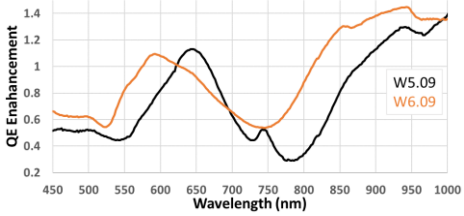

Figure 5. QE enhancement of the two samples with Ag nanograting with respect to the reference PD as a function of wavelength.

worth noting that the experimental QE reproduces the main features of the simulated absorption spectrum (orange curve in Fig. 2a), even if the "Fano-like" peak predicted by the simulations at 950 nm is less pronounced and blue-shifted. A more detailed analysis suggests that the difference between simulated and measured QE in the NIR spectral region is mostly due to the difference of dielectric film and metal thicknesses of the samples with respect to the optimal values suggested by numerical simulations. Even if the performance of the first prototypes are still far from the ideal case suggested by numerical simulation, the QE enhancement in the NIR region reaches the 45% at 950 nm in the case of the sample W6.09, a very remarkable result that pave the way for further optimizations.

5. FUTURE PROJECT VISION

During the phase 1 of the ATTRACT project we demonstrated that the integration of plasmonic nanostructures has the potentiality to increase the detection efficiency of SPADs and SiPMs in the NIR spectral range well above the state-of-the-art. We produced a proof of concept of the proposed detector and we validated the micro-nano integration technology by means of laboratory experiments, leading the project to a TRL of 3-4.

Following the successful implementation of the proof of concept in phase 1, the project has a good potential to evolve in a larger project in the framework of the ATTRACT phase 2.

5.1. Technology Scaling

In the phase 2 the project will have the ambitious goal of scaling up the present proof-of-concept to a TRL 5-7. The final aim will be the implementation of the described technology in a real SiPM production, qualified with the industrial standard used in the field. This activity could be carried out at the FBK microfabrication facility where a complete CMOS line is available. The ability of FBK of driving industrial developments in the field of SiPM has been already proven in the past, when the NUV-HD SiPM technology, developed at FBK has been subsequently transferred to an external foundry for mass production [7].

Moreover, starting from the proof-of-concept produced in the phase 1, additional work will be done to optimize the present structure to further increase the performance and to find new designs and new materials that are fully CMOS-compatible. In particular, using aluminium instead of silver to produce the nanograting would have a great advantage in terms of CMOS-compatibility, thus leading to a drastic reduction of the production costs down to 10\$/cm^2 for the bare (not-packaged) SiPM.

In the detail, the main steps envisioned in the phase 2 are:

- Numerical simulation campaign to optimize the design and investigate new materials, targeting a full-CMOS compatible process;
- Production of at least three SiPMs batches with integrated plasmonic nanogratings;
- Experimental characterization of the produced samples by following assessed industrial standards (including all the tests required for automotive and medical applications);
- Characterization of the produced devices in real applications and under operational environments (automotive and biomedical applications)

5.2. Project Synergies and Outreach

The PlaSiPM project is now composed of two partners: FBK, which has been dealing with the SiPM design and development, and IMB-CNM, CSIC that contributed with its expertise in the field of nanotechnology and carried out the nanostructures fabrication. In the phase 2 we will reinforce the consortium by including new academic and industrial partners. On one side, we are already in contact with the Group of Magnetic Nanomaterials at the University of Barcelona, that will contribute with its knowledge and expertise in designing plasmonic structures for molecular and chemical sensing, thus providing an important contribution to the project regarding the biomedical applications. One additional group expert in biochemistry and biomedicine will be incorporated, through the collaborative network of IMB-CNM, that has wide expertise in sensor development and integration. On the other hand, the presence of an industrial partner in the field of sensors and microelectronics will enforce the activity related with the characterization of the detector in operational environments by following industrial standards.

FBK is already collaborating with Avago Technologies GmbH (Germany) and LFoundry (Italy) on SiPMs development, therefore, they would be good candidates to join the collaboration. The consortium would also take advantage from the collaboration with the ATTRACT project PHOTOQUANT. The goal of the latter is to enhance the SiPM performance by using light trapping structures and metamaterials, and it is facing with similar technology challenges.

As already demonstrated during the first phase, our project will continue to disseminate the project results in scientific conferences, public seminars in universities and research institutes and in peer-reviewed journals.

5.3. Technology application and demonstration cases

This project aims at obtaining a SiPM with high NIR efficiency and ultra-fast timing resolution. There is a plethora of real applications that could take advantages from these developments. Among the others, two applications will be used as demonstration cases: autonomous driving and biosensors. Both the applications have a great societal impact in the field of health, smart and green transport and climate changes.

The proposed sensor has the potential to improve the performance of LiDAR systems for autonomous driving, thanks to the enhanced efficiency in detecting NIR photons, much higher than the current available devices.

A big innovation potential of such a sensor is also envisioned in the field of biosensors. The use of plasmonic structures as biosensing devices is widely used and it is now considered a well-known technique to detect molecules with a high grade of specificity. In the proposed detector, the plasmonic structure is directly integrated on a high-sensitivity detector and it could be considered a perfect candidate to be used as a biosensor. If the plasmonic surface of the detector (properly designed) is being functionalized with the appropriate antibodies, it could be used as a high-sensitive and compact system that combine in a single chip both the detecting and the sensing capabilities. Such a detector would be a unique and innovative solution in the field.

5.4. **Technology commercialization**

The presence in the consortium of industrial partners is a key aspect to reach a market-driven development of the detector. After the production of the functional SiPMs at the FBK facility, the industrial partners will be involved to quantify the resources needed to reach a commercial readiness level (TRL 7-8), and to develop a plan for the post-ATTRACT phase 2.

5.5. Envisioned risks

Some technological risks that could have an impact on the activities planned in the ATTRACT Phase 2, have been identified. For each risk a mitigation strategy is here proposed:

- The performance of the detector is lower than predicted by the numerical simulations. This could be due to the high sensitivity of the resonant mechanisms with respect to geometrical and material parameters. *Mitigation strategy:* a simulation campaign can be used to evaluate the dependence of the sensor performance with the process-related variabilities. The final design will be chosen by considering also the device robustness with respect to the fabrication process, and not only performance records.
- The final characterization shows that the sensor does not perform well under operative conditions because of some aspects were not considered during the design (i.e. real beam divergency, light polarization, operational temperature, etc…). *Mitigation strategy:* a preliminary discussion with the application experts could help in considering all the aspects of the final application since the first stage of the sensor development.
- The nanostructure is not realizable with the appropriate throughput for industrial applications. *Mitigation strategy:* Lithography would be performed by means of DUV lithography or by emerging technologies like as nanoimprinting that are now considered a viable and low-cost solution for mass-production of metallic nanostructures.

5.6. Liaison with Student Teams and Socio-Economic Study

In the first phase of the project, one master student (MSc) and two PhD students were actively involved in the project activities. This led, until now, to the production of one MSc thesis and one PhD dissertation focused on the project topic. In the second phase of the project we will further increase the involvement of MSc students, by offering new thesis proposals, and by organizing specific working groups focused on the project main topic and its related applications. We will invite the students in providing new ideas and solutions inspired by the project technology for addressing the most important societal challenges, and they will be invited to discuss the proposals with the project members. The presence in the project of universities from different countries will also promote the collaboration among students from different universities.

6. ACKNOWLEDGEMENT

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7. REFERENCES

[1] C. Piemonte et al., "Performance of NUV-HD silicon photomultiplier technology, " IEEE Transactions on Electron Devices, vol. 63.3, pp. 1111-1116, 2016.
[2] F. Acerbi, G. Paternoster, A. Gola, N. Zorzi and C. Piemonte, "Silicon photomultipliers and single-photon avalanche diodes with enhanced NIR detection efficiency at FBK," Nucl. Instrum. Methods Phys. Res. A,vol. 912, pp. 309-314, 2018.
[3] P. Berini, Laser and Photonics Reviews, vol. 8.2, pp. 197-220, 2014, DOI: 10.1002/lpor.201300019.
[4] Lumerical Inc. https://www.lumerical.com/products/.
[5] A. Hessel and A. A. Oliner,"A New Theory of Wood's Anomalies on Optical Gratings," Appl. Opt., vol. 4.10, pp. 1275-1297, 1965.
[6] A. Filippi, "Improving Silicon Photodetectors NIR Responsivity via Hybrid Opto-Plasmonic Resonances" PhD diss., Universita' degli Studi di Padova, 2020.
[7] P. Organtini et al., "Industrial exploitation of SiPM technology developed for basic research", nucl. Instr. And methods A, vol. 978, 2020.