# PHOTOQUANT

## Nano-photonics applied to ultrafast single photon quantum sensors

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### *ABSTRACT*

The PHOTOQUANT project demonstrated that a Silicon photo-multipliers with nearly 100% photo-detection efficiency, picoseconds single-photon time resolution and reduced primary/correlated noise, is a practicable reality. Simulations and measured results show that, using both a light concentrator and including light trapping features in the device stack, the photo-electron generation can be confined in a region as small as $820 \times 780 \times 500\ nm^3$, which will greatly improve the single-photon time resolution and the sensitivity of the device. The societal value of such an achievement will be tremendously high in a plethora of fields, from automotive, medical devices and cancer diagnoses to high energy physics.

SiPM; PDE; efficiency; SPTR; time resolution.

## 1. INTRODUCTION

Silicon photo-multipliers (SiPMs) are 2-D arrays of single photo-avalanche diodes (SPADs), nowadays limited for what concern the design flexibility in the search for better overall performances. Several applications would require a single photon time resolution (SPTR) FWHM of 10 ps, or even less, and a photo-detection efficiency (PDE) as close as possible to 100%. Such steps require a break with traditional methods and the development of novel technologies.

Key enabling features related to this project are:

- SiPMs with close to 100% photo-detection efficiency at lower over-voltage and unprecedented cell density, with consequent improvement in sensitivity, temporal properties, and linearity.
- Better single-photon time resolution (SPTR) across the entire SiPM surface for timing applications.
- Lower correlated and primary noise for cleaner pulse shapes and data analysis.
- Higher radiation tolerance for harsh environment applications.
- Lower power consumption.

SiPMs are extensively used in many cutting-edge fields, and the above-mentioned improvements are very often the driving force to reach important breakthrough in those fields. In time of flight (TOF) positron emission tomography (PET), a precise, low noise localization of the tumour can be delivered with a better coincidence time resolution (CTR) of the detectors, strongly influenced by the SiPM SPTR and PDE [1]. CTR in the order of 10 ps would greatly improve the current image quality or significantly reduce the dose injected into the patients [2]. Other TOF techniques used in high energy physics, astrophysics and nuclear physics, are strongly limited by the performance of the SiPM and on its future development towards better spectral sensitivity (UV for liquid-noble gases experiments) and better SPTR [3]. High energy physics will also strongly benefit from better timing and radiation hardness of the material proposed in this work. Automotive industries are expected to profit from this technology for LIDAR applications, which are recently setting challenging requirements in sensitivity and time resolution and for which SiPM are considered to be well suited [4].

The work presented here, and developed under the ATTRACT project PHOTOQUANT, will impact those fields with two key enabling technologies. First, simulations and measured results demonstrate how, using a light concentrator, a concentration factor of 8 can be achieved, redirecting the EM field in an area as small as $820 \times 780\ nm^2$ (along X and Y, the plane of the SPAD).

This new EM distribution allows for great SPAD layout flexibility with several advantages. Second, with this work, we introduce and simulate a new concept of SPAD with broadband light trapping behaviour, compatible with the concentrator design and capable of enhancing and confining the photo-electron conversion in 500 nm region along the Z coordinate of the SPAD. This will grant for a smaller thickness of the Silicon active layer (usually few microns), increased radiation hardness and reduced time jitter in the development of the avalanches, with consequently better SPTR.

## 2. STATE OF THE ART

In spite of impressive progress made in the last decade by several manufacturers, the SPTR of SiPMs is still in the range of 70-120 ps FWHM. Moreover, if the PDE can reach values of about 65 % in the visible, it is limited to about 20 % in the UV and to as low as 10 % in the NIR.

The PDE of a SiPM is, at first approximation, the product of three terms:

$$PDE = FF \cdot QE \cdot P_t$$

in which FF is the fill factor, QE the quantum efficiency and $P_t$ the avalanche triggering probability of the photo-generated carriers. FF is heavily affected by the reduction of cells size, which would be otherwise preferable because of higher cell density, linearity, faster recharge time and lower correlated noise. The latest generation technology developed by FBK (RGB-UHD) investigated FF enhancement together with the possibility of going to extremely small cell size (5 μm). Several technological constraints were found: (i) the real FF is lower than the layout FF, because of additional dead border caused by a lower electric field and poor charge collection at the edges of the high-field region. (ii) extreme reduction of space used for electrical isolation structures between cells, aiming at increasing FF in very small SPADs, causes an increased value of both primary and correlated noise. (iii) Using large size cells to increase the FF would imply working at a very high gain with the consequence of increasing the probability of correlated noise [5]. The degradation of FF has been experimentally proved also for several devices and is normally below 20 % for 5 μm cells for standard SiPM technology and can reach up to 40 % with FBK RGB-UHD technology, albeit with significant performance trade-off such as very high dark count rate (DCR).

## 3. BREAKTHROUGH CHARACTER OF THE PROJECT

The very physical limits of SiPM technology is approaching as far as cells size reduction is involved or when the time performance is a critical parameter for the application. It is therefore difficult to envision significant leap in performance in future generation devices without major structural changes, such as the ones designed in this project. Both the use of meta-material (MM) Gradient Index (GRIN) concentrator and light trapping will allow to break through these limits. Previous studies showed how to efficiently manipulate light using GRIN optics. Following the first example in the infrared region presented in [6], we designed MM GRIN for visible light (590 nm), to be applied to the SPAD entrance window for concentrating the light in the vicinity of the silicon active area, relaxing the layout constraint of the state of the art and allowing small cell sizes SiPMs to have high FF and high PDE at any given wavelength range. On the other hand, we show how, including a resonant grating and optimizing the thickness of the Si layer, it is possible to engineer the depth and homogeneity of carriers generation by light trapping, allowing to maximize Pt at any given photons wavelength [7] or over-voltage, therefore minimizing the SPTR and improving the PDE. Additionally, combining the use of these resonant modes with the features like high FF and small cells, it will be possible to bias the SiPM at higher over-voltage without incurring in the limit set by the divergence of correlated noise as in the current generation of SiPMs. At such high over-voltage, Pt will be close to 100 %.

These technological breakthroughs will enable many key objectives in several areas of interest [8]. In TOF-PET, and in combination with specially designed meta-scintillators, a CTR of 10 picoseconds FWHM will be achievable, allowing to get the direct 3D volume representation of the activity distribution of the radiopharmaceutical at the mm level without the need for tomographic inversion and introduce a quantum leap in PET imaging with a number of advantages [9].

100 % PDE and improved SPTR is of utmost importance for particle detector applications in high energy physics, nuclear physics, and astrophysics, all disciplines making great use of time-of-flight (TOF) techniques. Precise TOF resolution will enable 4D vertex reconstruction for pile-up rejection in high luminosity colliders. Particle identification is also using TOF and will greatly benefit from this technological breakthrough. Moreover, high PDE and superior SPTR will make LIDAR technology more precise, increasing the dynamic range thanks to the smaller cell size and allowing to detect objects with highly different reflectivity, making assisted and autonomous drive safer.

## 4. PROJECT RESULTS

The concentrator MM GRIN was created as a 2D square grating of holes with different diameters etched into a deposited layer of 500 nm $Nb_2O_5$. The focusing effect is generated by the refractive index gradient, with bigger holes in the outer region of the concentrator, as schematically shown in Fig.1a. Fig.1b report on an SEM picture of the final $Nb_2O_5$ concentrator produced on a $SiO_2$

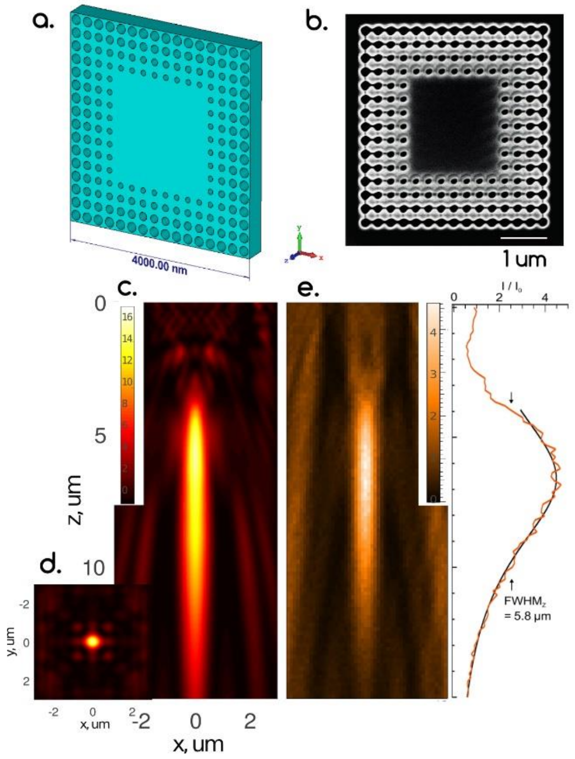

**Fig. 1.** a) Schematic representation of the concentrator. b) SEM picture of the FIB etched on Nb2O5. c) CST simulations of the concentrator response deposited on a glass substrate with n = 1.52, showing the intensity of the EM field in the X-Z plane normalized for the field impinging on the concentrator (I/I0). d) Same as c, but for the X-Y plane at the maximum value over Z (8.52 µm below the surface). e) Experimental characterization of the concentrator deposited on glass, using a scanning optical microscope with 590 ± 20 nm light incoming from the top of the image. The colour scale shows the intensity with the concentrator I normalized by the intensity without the concentrator I0. The inset on the right shows I/I0 as a function of depth Z, for X = Y = 0.

substrate, the same material used as SPAD entrance window. This concentrator has been optimized to work for 5 µm cell SPADs, dimension representative of the smaller FBK RGB cells technologically available. The average transmittance of the concentrator, across the entire surface, is 0.93, therefore minimal losses are introduced by the additional material. The results of CST studio suite simulations (CST) are compared with the measured data obtained using a scanning optical microscope. The comparison is shown in Fig.1c, d, e. The optical microscope was operated at 590 ± 20 nm, which matches the PDE maximum of the RGB SiPM technology. At the maximum of light concentration $I/I_0$ along Z (8.52 µm deep, dashed line in Fig.1e), the spatial distribution in FWHM was found to be 770 nm and 950 nm along X and Y (4.5% of the total area). The shift in the depth of the maximum with respect to the simulation is due to unbalanced deviations of the diameter of the hole along the concentrator plane. Simulations also demonstrated that the device is capable of concentrating light with wavelength between 490 and 690 nm. The concentration factor C, defined as the ratio of irradiance on the surface of the concentrator to the irradiance in the detection region [10], was evaluated to be equal to 5.

A similar approach was followed for a 15 µm SPAD cell, dimension selected for tests on a real SPAD, currently under evaluation. To enable a short focal length together with a large lens diameter, a refractive index profile made of 8 concentric sections was selected. The profile is shown in Fig.2a, together with a representation of the geometry of the holes used in the simulations (Fig.2b, notice the non-homogeneous hole diameter along z, a non-homogeneity expected from FIB milling). Fig.2c shows the concentrator produced on a $SiO_2$ substrate. Two optical microscope images are shown in Fig.2d and e, performed at 590 nm light illumination: on the top (Fig.2d), the microscope is focused on the concentrator surface, while the picture on the bottom (Fig.2e) is focused 7 µm below the surface, showing the light concentrated in the best focal plane. A concentration factor of about 8, together with a field described by $FWHM_x$ of 820 nm and $FWHM_y$ of 780 nm, show the ability of the MM GRIN lens to concentrate light. More details are presented is a recently submitted paper [11].

While the concentrator works to reduce the X-Y spread of the light, the exponential absorption along Z will still introduce a spread in e-h generation position. Fig.2f shows a proposed modified SPAD x-y section of 700x700 $nm^2$, with a Z dimension reduction of the Si layer down to 500 nm (RGB technology usually relies on several µm Silicon thickness) and a Silver grating applied to the bottom of the stack. Despite the small thickness, CST simulations of a periodical structure made of this elementary cell resulted in an absorption of ~1 in the Si layer, peaked around 590 nm (Fig.2g). Changing the Ag grating pitch and pillar dimension (700 nm and 420 nm respectively) will change the spectral sensitivity, giving the possibility to match it with a specific application. The power flux of the SPAD in Fig.2h shows the region where more likely the e-h pair will be created. Applying this technology to a 15 µm SPAD cell, meaning patterning the entire back surface with a periodical grating defined by the structure in Fig.2f, and combining it with a MM GRIN concentrator, will allow confining the avalanche generation to a region as small as $820 \times 780 \times 500\ nm^3$.

## 5. FUTURE PROJECT VISION

Following the successful implementation of the proof of concept (POC) in phase 1 and the results presented, this section will highlight the future steps we envision for this project, with the perspective of ATTRACT phase 2.

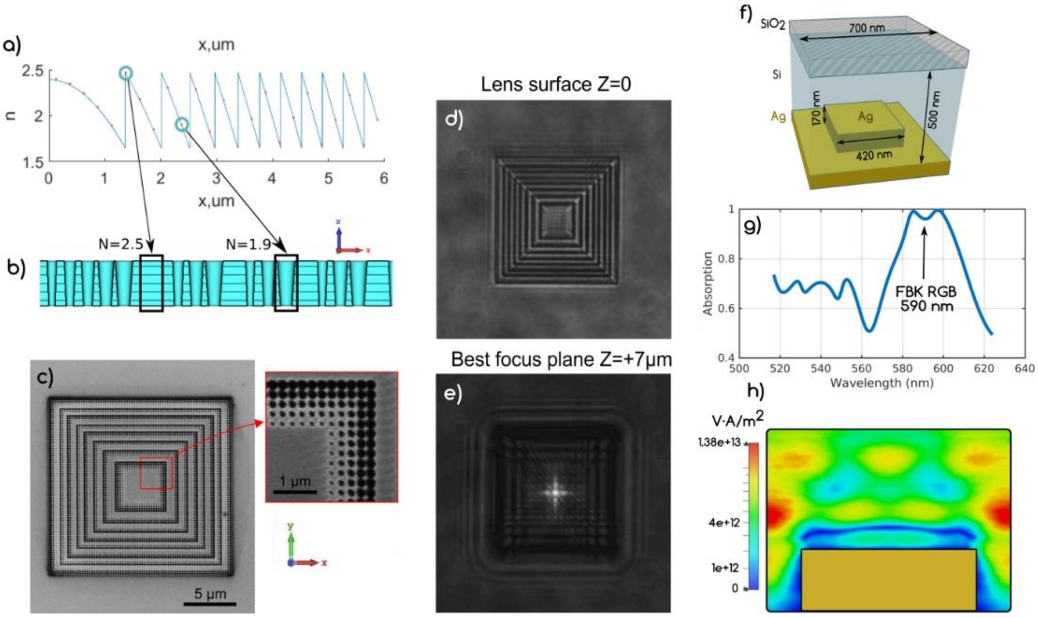

**Fig. 2.** Fresnel meta-lens with nano-holes milled in $Nb_2O_5$. (a) Index profile of the MM GRIN concentrator. (b) Holes cross section. (c) SEM image of the fabricated sample. 8 different concentric sections are present. The inset shows a high magnification view of one-quarter of the central section. (d) An optical microscope image taken at the concentrator surface, for Z = 0 µm. (e) Optical microscope image taken at the best focus of the concentrator, 7µm below the $Nb_2O_5$ surface. f) SPAD modified layout with reduced Si layer thickness and Ag grating on the bottom to improve absorption. g) Absorption spectrum, with Ag grating, optimized for 590 nm (FBK RGB technology). h) Power flux contour plot. The region of maximum flux corresponds to the region of maximal e-h generation.

### 5.1. Technology Scaling

The project will have to implement the POC inside a real SiPM production, both for the concentrator and the light trapping technology. The presence of FBK as a partner will ease this process thanks to the connection with industrial partners and the experience in developing innovative industrial production for SiPMs. Specifically, scaling up will require to substitute FIB milling with nano-imprinting, to reliably pattern the concentrator on a real size SiPM with cost-effective stamps. The same states for the light trapping technology, for which a scale-up will require not only the selection of a patterning technique suitable for periodical square arrangements, such as nano-imprinting, self-assembly or interference lithography, but also an ad hoc SiPM production to reduce the Si thickness down to the desired value.

### 5.2. Project Synergies and Outreach

The consortium will strengthen with another industrial partner, a foundry capable of integrating large scale patterning techniques, such as LFoundry (already producing some of FBK SiPM technologies), and a company who will make the business plan for our technology. Merging the consortium with the one belonging to the ATTRACT projects PlaSiPM and/or FastICpix is also being considered. The cooperation with PlaSiPM will have the common intent to modify the SiPM structure using light trapping, plasmonic and MM GRIN structures. Merging with FastICpix will instead aim at improving the SPAD to SPAD jitter, allowing to fully benefit from the PHOTOQUANT technology on a SiPM level.

As already widely demonstrated during the first phase, our project will continue to rely on conferences and peer-reviewed, open access articles for public dissemination. Oral presentation in the form of seminar will also be given in the consortium facilities, with specific attention to universities, through which MSc could be engaged.

### 5.3. Technology application and demonstration cases

This project aims at obtaining a working SiPM where each SPAD implements the technological concepts demonstrated during ATTRACT phase 1. The societal impact of such a device will arise from a leap in performance of the many different fields benefiting from the use of this new features , namely superior SPTR, 100% PDE at any given wavelength range, layout flexibility allowing for reduced noise with larger optical isolation and smaller active area, as well as higher radiation tolerance and lower power consumption. Additional characterization steps will be needed to evaluate the status of the project, which are already available in the FBK and CERN laboratories: SPTR measurements, dark count rate, cross talk, and irradiation tests, CTR measurements.

Following from these key technological advancements, concrete project deliverables for the next phase will include: 1) Experimentally demonstrate a 4-fold better coincidence time resolution in a TOF configuration representative of the final application of TOF-PET, LIDAR and high energy physics. 2) Experimentally demonstrate close to 100 % PDE for a LIDAR configuration, and a 2-fold PDE enhancement for scintillator applications. 3) By means of test beam and irradiation data, demonstrate a 3-fold improvement in the radiation hardness of the new SPADs.

### 5.4. Technology commercialization

Discussions are going on with a Swiss-based company, interested to take part to phase 2 of the project and to work along the preparation of a market study and a business plan for a commercial exploitation of our product. An important contribution of this company will be to quantify the resources needed to go from the present TRL3-4 of our device to a commercial TRL7-8, to patent and licence the key aspects of the technology and to seek for investors (venture capitalists, business angels). The objective will be to have a plan up to post-ATTRACT phase 2. As a complementary approach, we will look for private investors through the institutes already in the consortium, including the KT group at CERN, at CNRS in France as well as at INFN in Italy. Private-Public partnership could provide at the same time the open innovation structure that we are aiming at and the business management. In this view, the application to several European funding schemes is being considered (SME, FET, EUROSTAR), with priority to the one dedicated to such R&D&I phase of a project development.

### 5.5. Envisioned risks

Here is a list of the risks envisioned during the development of the second phase of this project:

- Risk: The inclusion of metallic part in the SPAD stack needs to be passivated, which could diminish the effectiveness of the light trapping approach, if too thick. There is an optimal value for which the trapping effect is still appreciable, and the metallic material does not constitute a problem for the normal functions of the SPAD. Mitigation: use of an all-dielectric configurations (without metallic parts), which have proven their effectiveness for other applications, are under study, which will be fully compatible with Si without the need for passivation.
- Risk: for a broad angular spread of the incoming light, light concentrator shows a drop in performance. Mitigation: the layout of the patterning can be optimized to match a specific angular distribution. Several applications will not have such a broad distribution.
- Risk: Covid19 could still influence the mobility and material delivery. Mitigation: during the preparation of phase 2, a careful plan will be redacted to rely as little as possible on these types of interactions.

### 5.6. Liaison with Student Teams and Socio-Economic Study

During the first phase, master students (MSc) were included in the project development described in the previous section. The second phase will boost this interaction in the direction of exploring PHOTOQUANT technology value beyond scientific and industrial applications. The students will be included in a highly motivating working group, supervised by an expert (possibly one of the students, depending on their background), with daily discussions and monthly challenges. A tight interconnection with the core project will be provided, with preparatory seminars and weekly reports from the MSc to the PHOTOQUANT core project. A good knowledge of the UN global challenges will be mandatory, qualified consultancy is under evaluation to periodically supervise the activity of the MSc group.

## 6. ACKNOWLEDGEMENT

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