Analysis of Photodiode Sensing Devices in a Photonic Integrated Chip solution for Quantum Computing

Luca Gemma
Department of Industrial Engineering
University of Trento
I-38123 Povo, Italy
Email: luca.gemma@unitn.it

Martino Bernard
Centre for Materials and Microsystems
Fondazione Bruno Kessler
I-38123 Povo, Italy
Email: bernard@fbk.eu

Mher Ghulinyan
Centre for Materials and Microsystems
Fondazione Bruno Kessler
I-38123 Povo, Italy
Email: ghulinyan@fbk.eu

Davide Brunelli
Department of Industrial Engineering
University of Trento
I-38123 Povo, Italy
Email: davide.brunelli@unitn.it

***Abstract*—From encryption to machine learning, the interest in quantum technologies is growing by the day. Many big companies are pushing the research and trying to develop a variety of techniques to achieve the so-called ”quantum supremacy.” Among all, there is one which is simpler to build an integrated system with: photonics. In this study, we illustrate the characterization for sensing elements of a prototype photonic integrated chip (PIC) where the photonic layer and the detector layer are homogeneously integrated. We fabricated in our facility a testing chip with silicon photodiodes as output devices. After the characterization discussed in this work, such detectors will be used as fully integrated sensing elements for a more advanced chip featuring thermistors as phase shifters in a multiple Mach-Zehnder Interferometers architecture.**

I. INTRODUCTION

Rigetti, IBM, Microsoft, Psy-Quantum, Ion-Q, D-Wave: all these giants of research are investing considerable resources to develop cutting-edge and scalable quantum technologies. At this time the research witnesses a variety of competing systems: superconducting, topological, photonic, trapped ions, each with its own pros and cons. Most of these system exploit entanglement and superposition of quantum states of photons on at least one stage. Such phenomena are fundamental for implementing a quantum system and, on a larger scale, quantum computers. Quantum systems, when large enough, can theoretically overcome the performance and limits of nowadays computing architectures by a large amount. Quantum technologies, however, are still mostly at the laboratory development stage, and they require much development in robustness and scalability to become real competitors of their traditional counterparts. Among all of the aforementioned systems, photonic systems are the closest to scalable integration thanks to the maturity of the silicon platform due to the huge success of microelectronics. Our study fits in this area, aiming to provide further characterizations for homogeneously integrated photonic circuits sensing elements: photodiodes (PDs). Generally, in a Photonic Integrated Circuit (PIC) a waveguide made by transparent glass medium is exploited to confine photons into a defined path. The path may be changed by acting on the waveguide with thermistors that locally change the temperature of the glass, and therefore the refractive index of the waveguide via the thermo-optic coefficient. The refractive index change in the waveguide in turn alters the phase of the travelling light. This tunability of the photons phase is exploited to realize engineered interference when multiple paths cross, e.g. in a 2×2 port (Beam Spitter, BS). By combining heaters and beam-splitters, it is possible to achieve any arbitrary unitary state transformation, granting photonic chips the fundamental property of universality. The last element of the chain is represented by sensing elements, like PDs, whose task is to correctly detect the quantum circuit’s output. In this work we discuss linear PDs detectors to demonstrate the feasibility of the process, but the same integration technology will be used to integrate advanced single-photon avalanche diodes (SPADs) for proper quantum state detection in the future. There are strong proofs of photonics as a solid platform for realizing quantum chips, like in Annoni et al. [1] where a photonic switch was built by assembling a matrix of Mach-Zehnder Interferometers (MZIs) through consecutive stages, granting the acquisition of high dimensions parallel data. MZIs were a central focus even in [2], where Gentile et al. designed and realized a Bayesian phase estimator that proved resilient to most common noise sources. Such structures have been further developed to realize programmable nano-photonic processors and general 2-qbit ports [3], [4]. However, such systems still rely mostly on off-chip sources and detectors, where the most popular integrated option features the use of superconducting nanowires operating at cryogenic temperatures. In this work, we aim at a first characterization for PDs embedded in a PIC solution, with the aim of further developing the technology into scalable room-temperature integrated single photon detectors. This work is organized as follows: in Section II we present a brief overview the of full quantum photonic chips where the detectors will be featuring as sensing elements. Section III illustrates our architecture of the present prototype device. In Section IV, we discuss our characterization results, focusing on the PDs response from external illumination. Finally, in Section V conclusions are drawn.

II. OVERVIEW

Literature defines Silicon Nitride (SiN) as state-of-the-art material for near-infrared photonic waveguides [5]. Being CMOS compatible, SiN offer an ideal platform for silicon photonic chips fabrication with an huge advantage with respect to chips based on non CMOS-compatible materials. In this work we integrate silicon photodetectors in the substrate of a PIC realized using SiN as the guiding material. Having the detector directly integrated in the silicon substrate has huge advantages with respect to other quantum technologies such as trapped ions or superconducting circuits that require specific and dedicated fabrication processes for the deposition and fabrication of exotic materials. The SiN waveguide fabrication process can have different basic building blocks embedded in the circuits. Such blocks are usually made, among other components, by at least one beam splitter. The building block we focused on in our work was the Mach-Zehnder interferometer. Generally speaking, an MZI includes two beam splitters and two-phase shifters placed on two different and parallel traces of a waveguide. After the first beam splitter, the light is divided into a 50-50 power split, and their paths are further modified by a phase change induced by thermistors. Lastly, the two light beams travel through a second beam splitter and exit the block forming interference. We have already characterized Ti-TiN thermistors as phase shifters in a previous work [6]. Here we will characterize integrated PDs to be used as photon detectors in the PIC. In this work we will measure the characteristics of the photodiodes and obtain the spectral responsivity from (external) normal incidence. This responsivity will later be used to estimate the detection efficiency of the PDs from in-plane excitation coming from the PIC. High detection efficiency is required to fully design and implement a PIC solution embedding up to 10 MZIs and correctly detecting the output beams with an array of such diodes.

III. THE ARCHITECTURE

We fabricated a test structure with silicon PDs in the cleanroom facility of Fondazione Bruno Kessler (FBK). The chip was realized with non-stoichiometric SiN as the photonic material, and the fabrication process is similar to that of the the test chip for Ti-TiN thermistors in our previous study [6]. We used a silicon wafer with an epitaxial layer for the detectors, built through ion implantation and covered with SiO_2 glass. A silicon oxide layer is used both below and above the photonic layer to insulate the guided modes from the silicon substrate and external environment respecrively. The final PIC will include both silicon PDs (as output detectors) and Ti-TiN thermistors (as phase shifters). An electronic control board is necessary to get full control of all PIC features. In the following section, the response of the PD to external excitation is presented and discussed.

IV. RESULTS

The PDs characterization was performed with a 200mm 4x PH150 Karl-Suss PM8 Manual Probe Station, ensuring high stability and reliability. In addition, a LABVIEW VI was designed to collect the data.

First, dark condition I-V curve was measured to estimate the breakdown voltage. The behavior in the breakdown region is shown in Fig. 1 for six of our silicon PDs, giving a breakdown voltage value close to -29 V. The forward current of the diodes was also tested in dark condition, as shown in In Fig. 2 with all of the diodes bearing a current intensity of mA without damage. Secondly, a set of measurements with a light source was performed to check the PD response under normal incidence illumination. Figure 2 shows I-V curves of a diode under different illumination conditions.

In this first study, the light intensity response was obtained by changing both the illuminator current and the optical zoom of the microscope through which the light beam passed. The flux is thus roughly proportional to the illuminator intensity times the zoom factor squared. The current intensity for a null voltage bias, i.e. the photovoltaic current, is plotted against the illumination intensity in Fig. 2. Notice that, as expected, such a current is roughly linearly related to optical intensity.

Finally, the normal-incidence spectral responsivity of the PDs was quantitatively characterized by using a spectral lamp, a spectrometer and a calibrated detector. Figure 2 shows the A/W spectral responsivity in the visible and near infrared region for three PDs of different dimension (width: 98 μm, variable length: 112, 177 and 242 μm). The optical power flux impinging on the detector was first measured spectrally by using the calibrated detector. Then, the photocurrent at 0 V bias was measured on our PDs and normalized on the impinging power. Note that the three detectors have different active areas, but the observed normalized responsivity is the same. The responsivity values at 700 nm and 850 nm of wavelength, where the PDs will be characterized for co-planar light propagation in the photonic circuit in future experiments, are highlighted in Fig. 2. The oscillating spectral features with ~50 nm period are due to thin the film interference in the various layers that cover the detector. It is worth noting that these features will vanish in the next characterization stage, where the light will be directly coupled from the waveguides to the detector.

V. CONCLUSION

In this paper, we illustrated the characterization curves for a set of silicon PDs monlithically integrated with a Silicon Oxynitride SiON PIC. The next step will be the characterization of the PD response from in-chip light travelling inside the waveguides of the PIC. Such devices will be included in our future prototypes of complex PICs. Our results demonstrate the effectiveness of the produced silicon diodes both for dark and bright current regimes, thus confirming the viability of the chosen fabrication technology. The PDs responsivity guarantees that, provided an adequate coupling with the PIC, sub dBm photonic signals can easily be detected with common electronics. Together with our previous inspection on resistive Ti-TiN thermistors as phase shifters for non-stoichiometric SiON optical waveguides in [6], this paves the way for an electronic circuit meant to control precisely the PIC, exploiting feedback solutions in both linear optic (with PDs) and quantum regimes (with APDs).

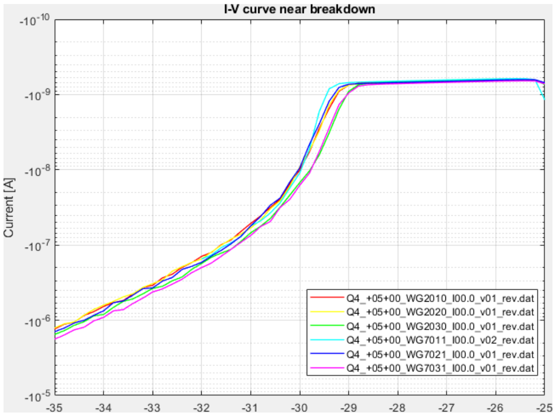

Fig. 1: Typical I-V curves near breakdown.

ACKNOWLEDGMENT

We acknowledge the support of Giovanni Paternoster (FBK) for the design and realization of the PDs, as well as the support of the Microfabrication Laboratory staff of FBK during sample fabrication. We further acknowledge financial support from the Autonomous Province of Trento, under the initiative *"Quantum at Trento - Q@TN"*, projects *Q-PIXPAD* and *CoSiQuP*. This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 777222, Attract *INPEQuT*. Moreover,this work was supported in part by the Italian Ministry for Education, University and Research (MIUR) under the program "Dipartimenti di Eccellenza (2018-2022)".

REFERENCES

[1] A. Annoni, E. Guglielmi, M. Carminati, S. Grillanda, P. Ciccarella, G. Ferrari, M. Sorel, M. J. Strain, M. Sampietro, A. Melloni, and F. Morichetti, "Automated routing and control of silicon photonic switch fabrics," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 22, no. 6, pp. 169–176, Nov 2016.

[2] A. A. Gentile, S. Paesani, R. Santagati, J. Wang, N. Wiebe, D. Tew, J. L. O'Brien, and M. G. Thompson, "Noise resilience of bayesian quantum phase estimation tested on a si quantum photonic chip," in *2017 Conference on Lasers and Electro-Optics Europe European Quantum Electronics Conference (CLEO/Europe-EQEC)*, June 2017, pp. 1–1.

[3] X. Qiang, X. Zhou, J. Wang, C. M. Wilkes, T. Loke, S. O'Gara, L. Kling, G. D. Marshall, R. Santagati, T. C. Ralph, J. B. Wang, J. L. O'Brien, M. G. Thompson, and J. C. F. Matthews, "Large-scale silicon quantum photonics implementing arbitrary two-qubit processing," vol. 12, no. 9, pp. 534–539. [Online]. Available: http://www.nature.com/articles/s41566-018-0236-y

[4] N. C. Harris, J. Carolan, D. Bunandar, M. Prabhu, M. Hochberg, T. Baehr-Jones, M. L. Fanto, A. M. Smith, C. C. Tison, P. M. Alsing, and D. Englund, "Linear programmable nanophotonic processors," vol. 5, no. 12, p. 1623. [Online]. Available: https://www.osapublishing.org/abstract.cfm?URI=optica-5-12-1623

[5] C. G. H. Roeloffzen, M. Hoekman, E. J. Klein, L. S. Wevers, R. B. Timens, D. Marchenko, D. Geskus, R. Dekker, A. Alippi, R. Grootjans, A. van Rees, R. M. Oldenbeuving, J. P. Epping, R. G. Heideman, K. Wörhoff, A. Leinse, D. Geuzebroek, E. Schreuder, P. W. L. van Dijk, I. Visscher, C. Taddei, Y. Fan, C. Taballione, Y. Liu, D. Marpaung, L. Zhuang, M. Benelajla, and K. Boller, "Low-loss si3n4 triplex optical waveguides: Technology and applications overview," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 24, no. 4, pp. 1–21, July 2018.

[6] L. Gemma, M. Bernard, M. Ghulinyan, and D. Brunelli, "Analysis of control and sensing interfaces in a photonic integrated chip solution for quantum computing," in *Proceedings of the 17th ACM International Conference on Computing Frontiers*, ser. CF '20. New York, NY, USA: Association for Computing Machinery, 2020, p. 245–248. [Online]. Available: https://doi.org/10.1145/3387902.3394034

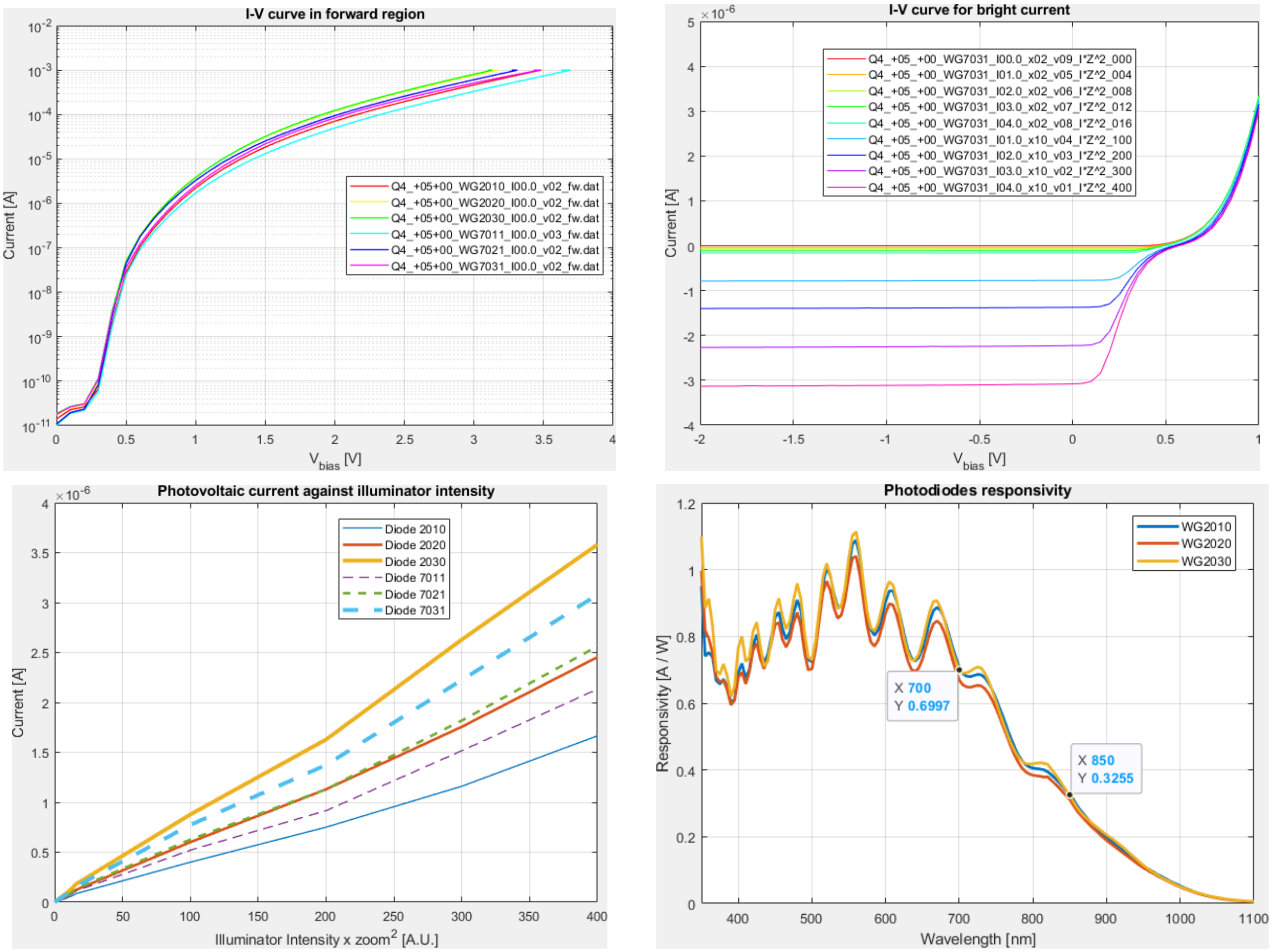

Fig. 2: Top left: I-V curve in forward region. Top right: I-V curve for bright current. Bottom left: I-V curve in photovoltaic mode for different illumination conditions. Bottom right: Measured A/W responsivity of the fabricated PDs.