A monolithic electronic-photonic integrated quantum simulator platform at NIR and room-temperature operation

M. Ghulinyan, M. Bernard, F. Acerbi, G. Piccoli, G. Paternoster, Y. Kwon, L. Limongi, M. Zyskowski, and G. Pucker

Centre for Sensors and Devices, Fondazione Bruno Kessler, Italy

ghulinyan@fbk.eu

Abstract: We have designed and built a reliable Quantum Simulator prototype by combining silicon microelectronics and silicon nitride quantum integrated photonics into a unique semiconductor platform. Our device operates at NIR wavelengths and at room-temperature conditions.

A cornerstone for the future of experimentation, simulators allow real-world scenarios and conditions to be explored without the associated risks, costs, or time restrictions imposed by the real world. Integrating the nature and behavior of matter and energy on atomic scales creates a more authentic virtual world in which simulations can run following the rules of quantum mechanics to model new smart materials, predict chemical reactions, or solve high-energy physics problems. However, the ways to access quantum behaviors are often hampered by the need for complex conditions and costly solutions. FBK is creating a lab-accessible and affordable quantum simulator (QS) operable at room temperature. Such a QS has the potential to provide many advantages including supporting rapid and widespread innovation.

We have designed and built an affordable, easy-to-use, reliable QS prototype (Fig. 1). Our vision to create a QS is being achieved by combining silicon microelectronics and silicon nitride quantum integrated photonics into a unique semiconductor platform, to produce a breakthrough device. A 3D-integrated QS hardware is being developed, involving *reconfigurable photonic quantum interference circuits* (Fig. 2a), monolithically integrated onto a silicon chip with *scalable arrays of single photon avalanche detectors* (silicon SPADs, Fig. 2b,c) operable at ~800 nm wavelength and at room temperature. The reconfigurability of the quantum optical architecture is provided by tiny micro-heaters which allow hundreds of optical phase-shifting elements to be set within ~1 cm^2 area chip. This allows the flow of single-photons – the qubits – to be directed along different paths creating sequences of quantum logic gates, the equivalents of transistors in an integrated electronic circuit.

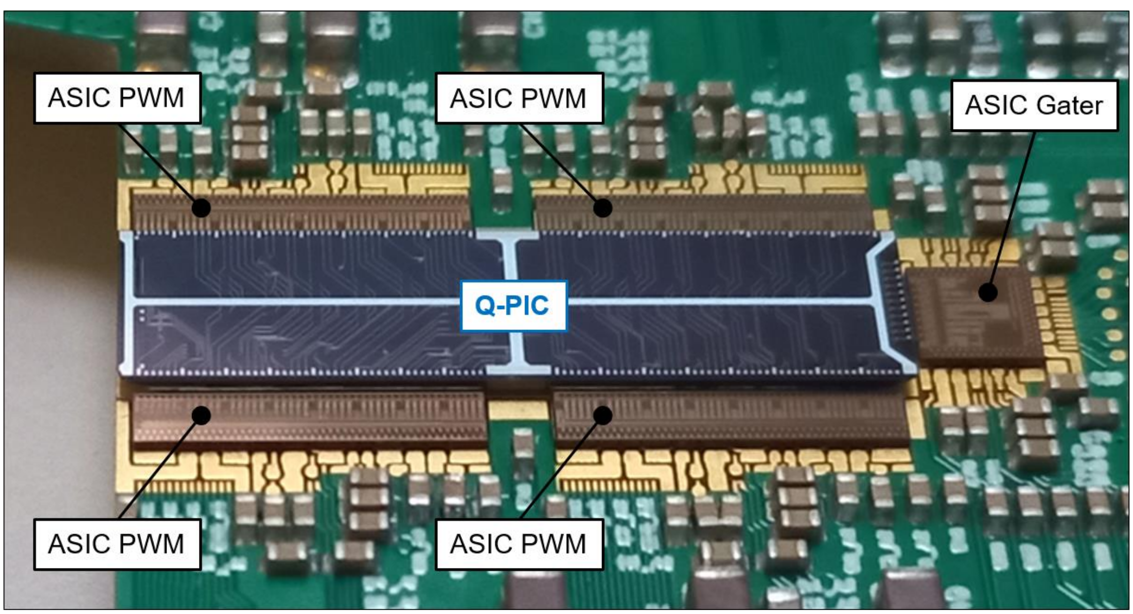

Figure 1. The QS and control electronic chips mounted on the PCB board.

In parallel, a customized software set of quantum algorithms, that can sustain the quantum simulation hardware results, is being built. Through this, the quantum hardware is accessed via an HTML interface where users can set the desired problem to be run on the QS. An external electronic chip drives the QS module to actively control the quantum optical circuit and collect the output data, i.e. photon detection from the single photon avalanche diodes, used to further feed and refine the software algorithm. Additional linear-mode monitoring photodiodes are integrated and used for precise system tuning.

This QS prototype will open the door to future developments in miniaturized and more complex quantum photonic integrated circuits and on-chip detectors of quantum states of light. As for the impact of the technology's application, it will enable new ideas and quantum functionalities to be tested on a single silicon chip, run remotely by a user from a PC. Most excitingly, the chips provide a means to explore new ideas in the field of quantum science and this novel and promising approach offers the chance for a ground-breaking, mass-manufacturable technology.

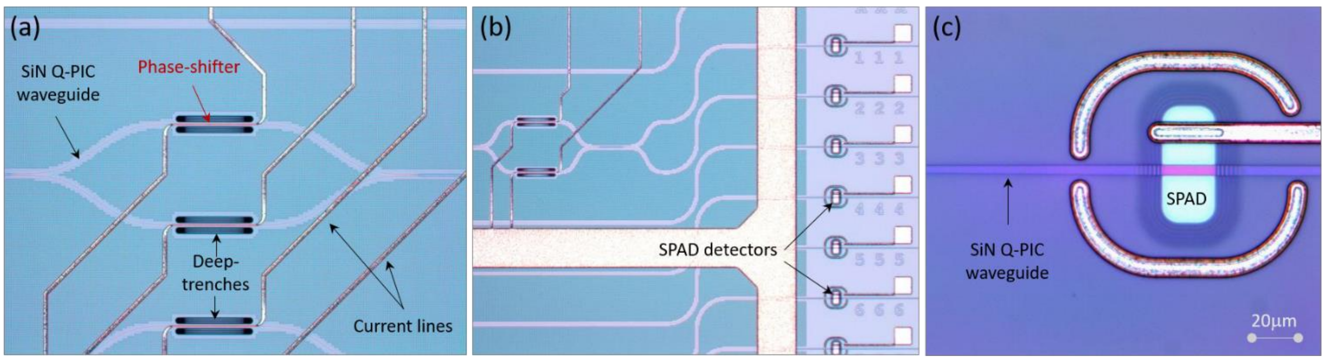

Figure 2. Optical microscope images of (a) the integrated Q-photonic circuit, (b) the PIC and the array of SPAD detectors and (c) the coupling region of the SiN waveguide and a single Silicon SPAD.

References

[1] M. Bernard, F. Acerbi, G. Paternoster, G. Piccoli, L. Gemma, D. Brunelli, A. Gola, G. Pucker, L. Pancheri, and M. Ghulinyan. *Top-down convergence of near-infrared photonics with silicon substrate-integrated electronics.* Optica **8**, 1363-1364 (2021). 10.1364/OPTICA.441496

[2] M Sanna, A Baldazzi, G Piccoli, S Azzini, M Ghulinyan, L Pavesi. *SiN integrated photonic components in the Visible to Near-Infrared spectral region.* Optics Express **32** (6), 9081-9094 (2024). 10.1364/OE.514505 (selected for Spotlight in Optics)

[3] F. Acerbi, M. Bernard, B. Goll, A. Gola, H. Zimmermann, G. Pucker, and M. Ghulinyan. *Monolithically Integrated SiON Photonic Circuit and Silicon Single-Photon Detectors for NIR-Range Operation.* J. Lightwave Technol. **42**, 2831-2841 (2024). 10.1109/JLT.2023.3342031

[4] G Piccoli, M Sanna, M Borghi, L Pavesi, M Ghulinyan. *Silicon oxynitride platform for linear and nonlinear photonics at NIR wavelengths*. Optical Materials Express **12**(9), 3551-3562 (2022). 10.1364/OME.463940

[5] Y. Kwon, M. Bernard, L. Limongi, G. Piccoli, M. Ghulinyan, and B. -S. Choi, *Full Software Control on MZI-Based Photonic Integrated Circuit*. IEEE Access **12**, 146291-146302 (2024). 10.1109/ACCESS.2024.3474014