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XXXVI Cycle

Experimental characterization of single photon devices for quantum technologies application and simulation of novel radiation sensors

Greta Andrini
Supervisor: Prof. Angelo Rivetti

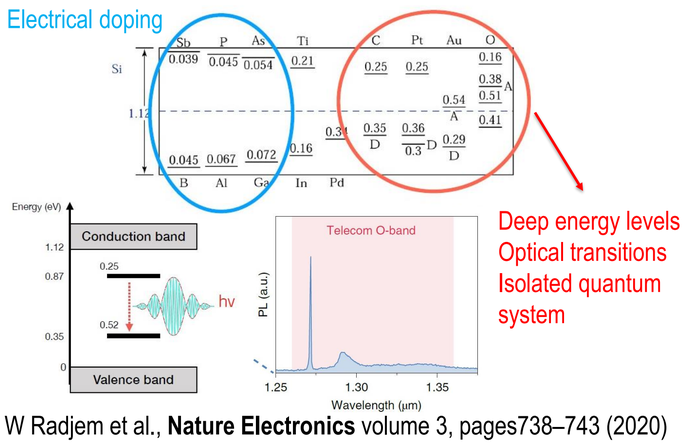
Research context and motivation

- Digital Assembly 2019: seven EU signed a declaration agreeing to explore together **how to develop and deploy a quantum communication infrastructure** (QCI) across the EU within the next ten years.
- 2018: €1 billion for the **Quantum Technologies Flagship**

From the Quantum Manifesto (May 2016)

Photonic quantum technologies:
- Quantum cryptography (QKD)
- Quantum computing (qu-bit)
- Quantum sensing

Ideal single photon sources:
- High emission rate – short lifetime
- Monochromatic emission
- High quantum efficiency
- Stable emission (no blinking)
- Scalable physical system
- **Telecom wavelength**

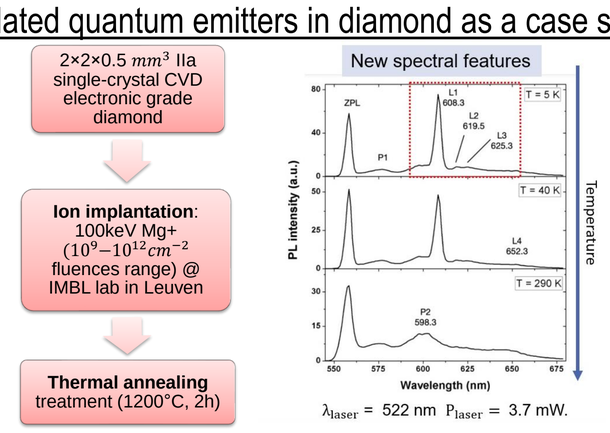


Deep energy levels
Optical transitions
Isolated quantum system

W Radjem et al., **Nature Electronics** volume 3, pages738–743 (2020)

Novel contributions

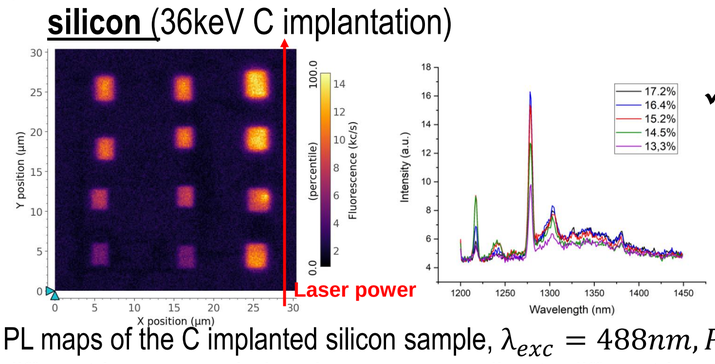
1) Assessment of a **single-photon sensitive cryogenic confocal microscope**: Mg-related quantum emitters in diamond as a case study



λ_{laser} = 522 nm P_{laser} = 3.7 mW.

- ✓ First **systematic experimental analysis** of the structural and **photophysical** properties of **MgV centers** fabricated upon ion implantation in artificial diamond [2] Previously unexplored emission properties have been demonstrated at cryogenic temperatures

2) Laser annealing activation of C-based emitters in **silicon** (36keV C implantation)



- ✓ Single-photon sensitive **cryogenic** confocal microscope (4-300 K) operating in the **IR** and VIS range
- ✓ Investigation of laser annealing protocol for colour centres activation in silicon (so far, any other contribution reported in literature)

PL maps of the C implanted silicon sample, $\lambda_{exc} = 488nm, P_{laser} = 2mW$ and PL spectra acquired in different laser annealed regions corresponding to different laser powers

Addressed research questions/problems

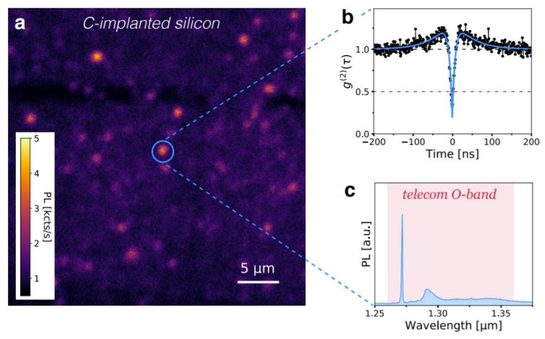
INFN QUANTEP project: Development and implementation of a complete Silicon Photonics Integrated Circuit for Quantum Computation with linear quantum optics circuits and single photons.

1. Identification of appealing classes of **emitter centers in the telecom C-band**
2. Ion implantation can unlock devices manufacturing through the **deterministic placement of emitters** registered to optical circuits

Colour centres in solid state materials (diamond, SiC, Si)

- ✓ Deterministic sources
- ✓ Compact (chip) size, portability, mass production
- ✓ Integration with existing micro-electronic technologies
- ✓ Low power consumption, environmentally friendly

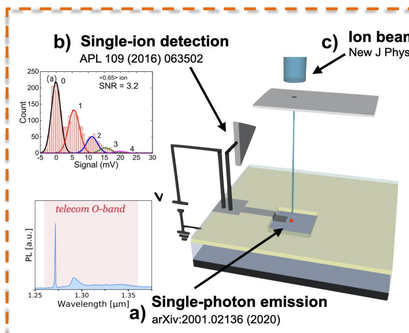
Silicon



Scalable silicon-based quantum photonics device

Bright **telecom wavelenght** single photon sources at Cryogenic temperature **(T<110K)**

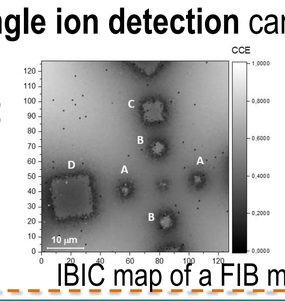
W Radjem et al., **Nature Electronics** volume 3, pages738–743 (2020)



Deterministic Implantation
- Nanoscale ion positioning
- Single ion delivery
- Formation yield

An irradiation chamber has been set up at the TO 100 kV ion implanter → reference structures on target sample itself to be used for **single ion detection** can be integrated

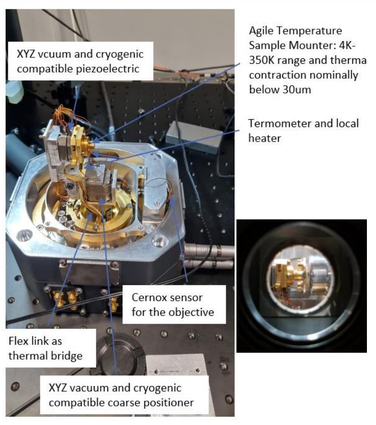
Ion Beam Induced Charge (IBIC) Technique:
- Single-ion sensitivity
- Same wafer to be processed by individual ions



In situ measurement of the ion microbeam resolution has been demonstrated [1]

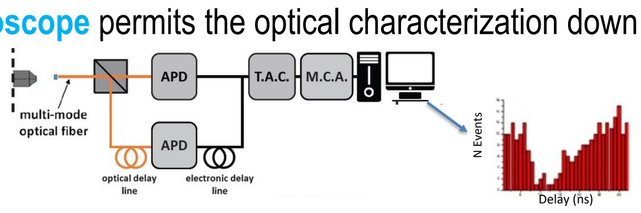
IBIC map of a FIB machined Si photodiode

Adopted methodologies

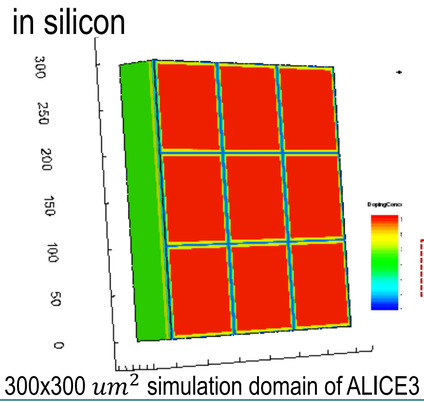


Hanbury-Brown & Twiss Interferometry for experimental measurement of second order autocorrelation function allows to identify and analyze single-photon emitters.

A closed-cycle optical cryostat by Montana Instruments together with a **single-photon sensitive confocal microscope** permits the optical characterization down to 4K.



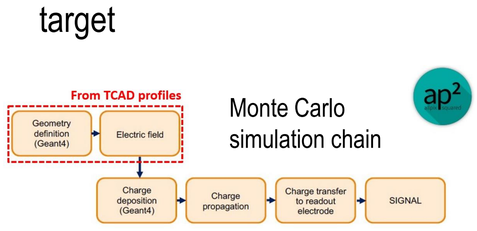
Technology Computer-Aided Design can be a valuable resource in the optimization of the target itself as a solid-state particle detector for the **deterministic positioning of impurities** in silicon



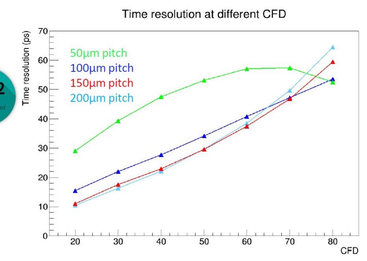
300x300 um^2 simulation domain of ALICE3 pixel sensors

Case study: ALICE 3 project

Optimization of Monolithic Active Pixel Sensors for particle identification via time-of-flight with 20 ps time resolution target

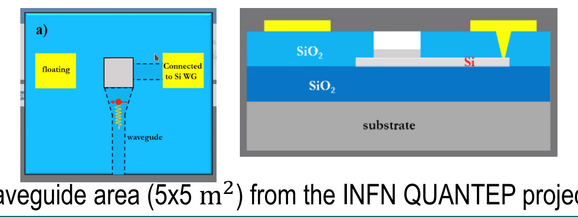


Monte Carlo simulation chain



Future work

- **Identification** of C-based **single-photon** emitters in Si
- **Activation** ot C-based **single-photon** emitters in Si with laser annealing process
- Comparison with standard annealing processes
- Deterministic placement of single photon emitters in a Complete Silicon Photonics Integrated Circuit:
  1) Sensor design?
  2) Suitable doping profiles?
  3) keV single ion signal estimation?



Sketch of exposed silicon waveguide area (5x5 m^2) from the INFN QUANTEP project

Submitted and published works

1. G. Andrini, E. Nieto Hernández, G. Provatas, M. Brajkovic, A. Crnjac, S. Ditalia Tchernij, J. Forneris*, V. Rigato, M. Campostrini, Z. Siketic, M. Jaksic, E. Vittone "*An ion beam spot size monitor based on a nano-machined Si photodiode probed by means of the ion beam induced charge technique*", Vacuum, vol. 205, no. 111392, 2022
2. E. Corte, G. Andrini, E. Nieto Hernández, V. Pugliese, A. Costa, G. Magchiels, J. Moens, S. M. Tunhuma, R. Villarreal, L. M.C. Pereira, A. Vantomme, J. Guilherme Correia, E. Bernardi, P. Traina, I. P. Degiovanni, E. Moreva, M. Genovese, S. Ditalia Tchernij, P.Olivero, U. Wahl, J. Forneris "Magnesium-vacancy optical centers in diamond", arXiv:2206.08670, June 2022

List of attended classes

- 02LWHRV – Communication(12/02/2022, 6.67)
- 01RISRV – Public Speaking(13/02/2022, 6.67)
- 01DMLKG – Introduzione all'ottica ed alle Tecnologie quantistiche(24/03/2022, 41.67)
- 01DOMKG– Introduzione alla microscopia ottica - Scienza e Tecnologia (didattica di eccellenza vp)(23/05/2022, 33.3)
- 01QRGRV– Microelectronics for radiation detectors I(29/06/2022, 30h, exam in October 2022)
- Summer School on Advanced Photonics and Electronics for Quantum and Space Application(29/8/2022, 14)
- Summer School on Ion Implantation Technology(22/09/2022, credits to be approved)

PhD program in
Electrical, Electronics and Communications Engineering