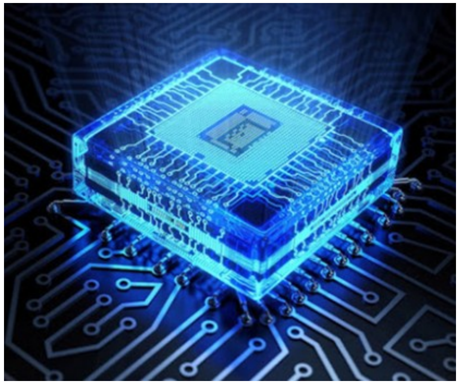
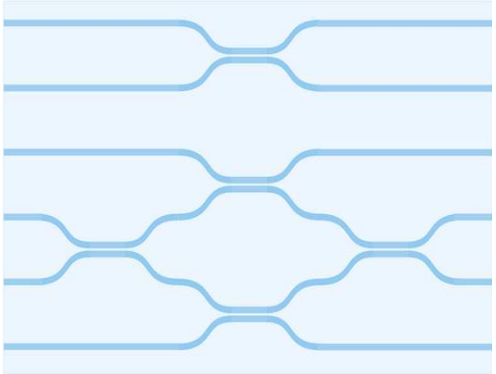
# QUANTEP
# QUANtum Technologies Experimental Platform

- **INFN** project on Quantum Technologies
- Started in 2021

**INFN Sections and Laboratories involved**: **LNL**, **MI**, **PG** (Camerino), **PI**, **PV** (Modena e Reggio Emilia), **RM2**, **SA**, **TO**

- Interest and support from: LNGS (LUNA-MV), LABEC (DEFEL), NEST, TYNDALL, Institut Ruđer Bošković (RBI), Micro Photon Devices (MPD), University of Leipzig, Chalmers University of Technology, Physikalisch-Technische Bundesanstalt (PTB).
- 15-17 FTE/year, up to ~ 1 MEuro budget
- Creation of a common **Silicon Photonics** platform for development and characterization of
  - quantum computing circuits;
  - single photon sources;
  - single photon detectors;
  - polarization control circuits.





# Universal Quantum Gates

**1 qubit:** $\alpha_0|0\rangle + \alpha_1|1\rangle, \ |\alpha_0|^2 + |\alpha_1|^2 = 1$

**Some 1 qubit elementary gates**

$$X = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \quad Z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \quad R_\phi = \begin{pmatrix} 1 & 0 \\ 0 & e^{i\phi} \end{pmatrix} \quad H = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$$

Pauli-X (NOT) gate | Pauli-Z gate | Phase shift gate | Hadamard gate

**2 qubits:** $a|00\rangle + b|01\rangle + c|10\rangle + d|11\rangle \quad |a|^2 + |b|^2 + |c|^2 + |d|^2 = 1$

**The prototype (universal) 2 qubits gate is the Controlled NOT (CNOT) gate**

control bit

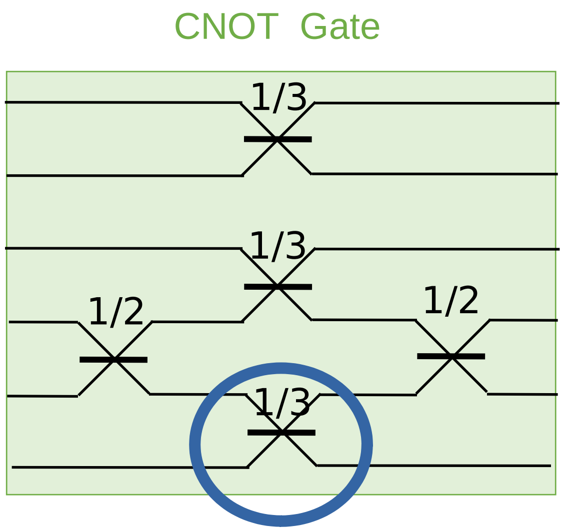
$$\mathrm{CNOT} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

target bit

- the control bit is left unchanged
- the output target bit is the XOR of the input control and target bits
- but of course it does much more: it works on the wave function

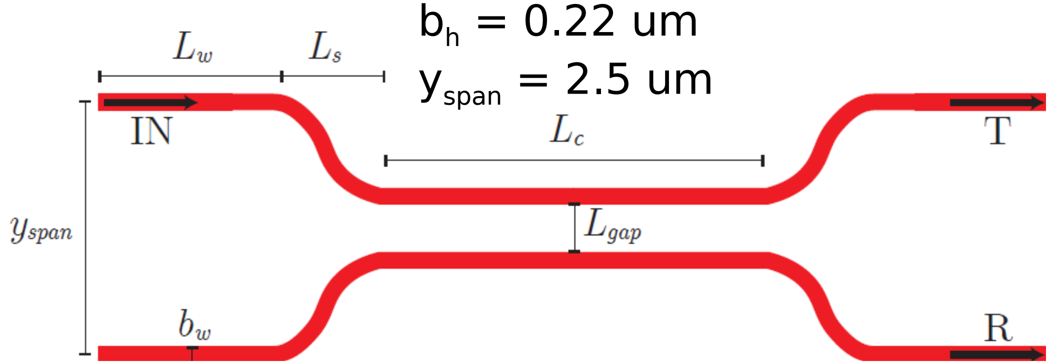
$$a|00\rangle + b|01\rangle + c|10\rangle + d|11\rangle \longrightarrow a|00\rangle + b|01\rangle + c|11\rangle + d|10\rangle$$

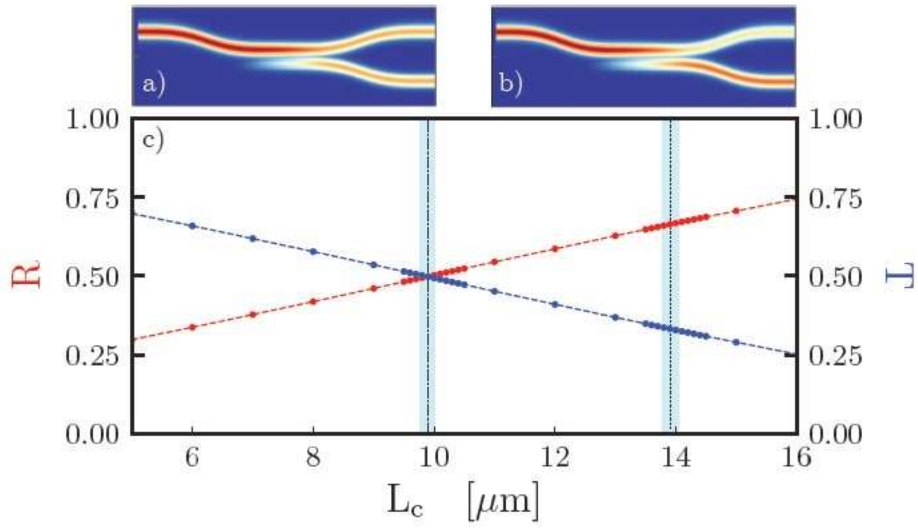
# Controlled-NOT gate

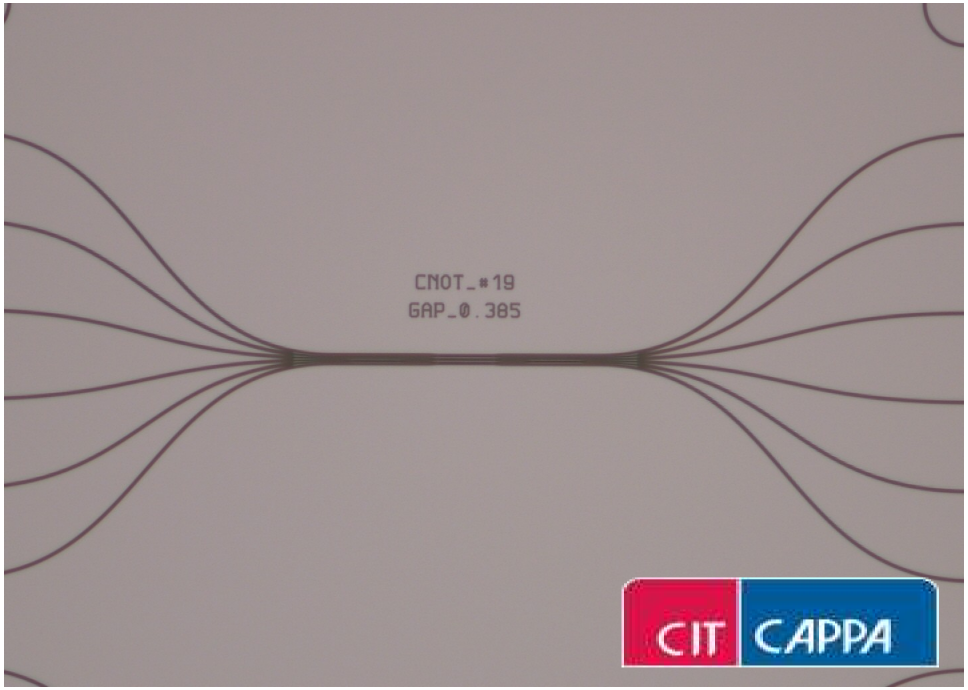



**Directional coupler**

**Directional coupler**
$b_w$ = 0.45 um
$b_h$ = 0.22 um
$y_{span}$ = 2.5 um

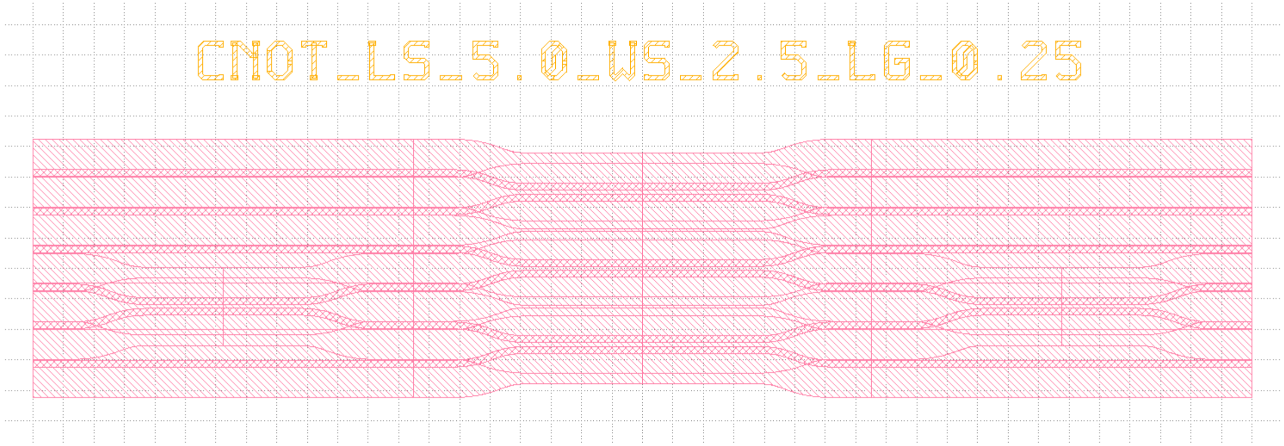


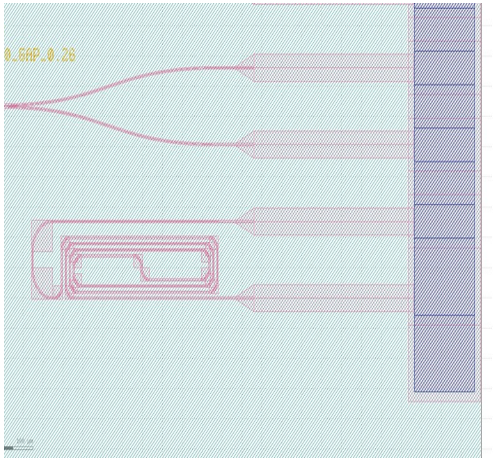



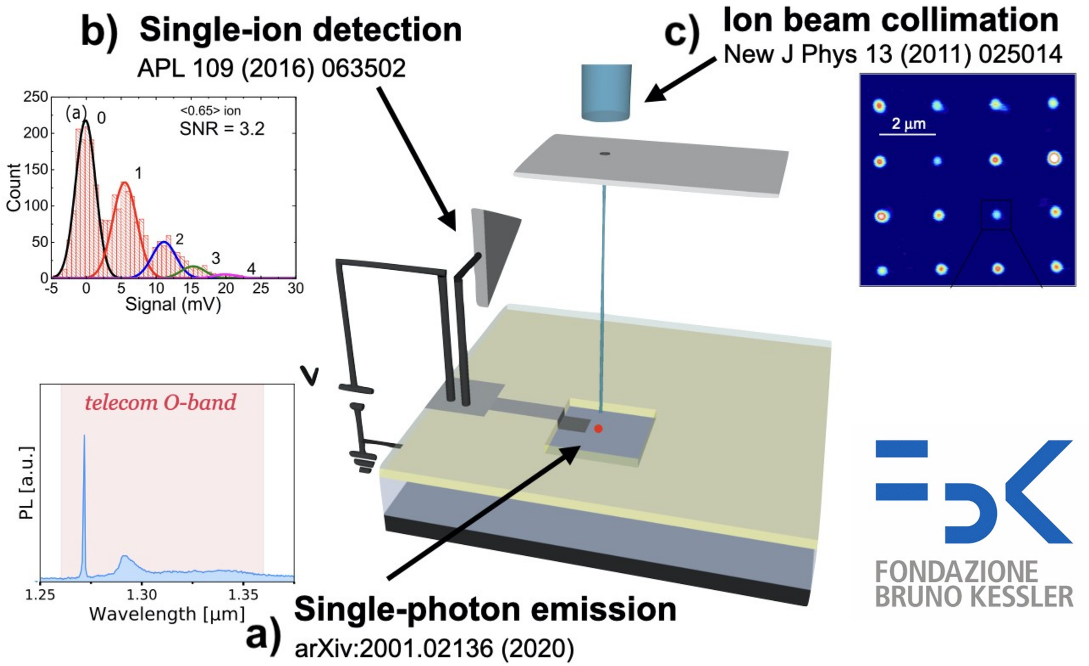
# Photonic Integrated Circuits

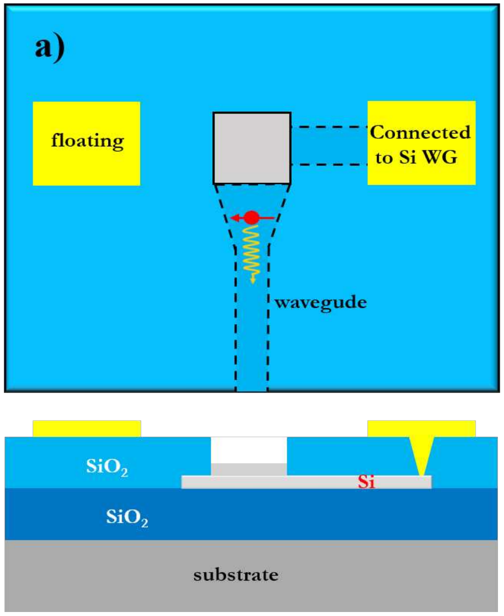
- Disegnati 6 chip fotonici
- Gap dei directional coupler 250nm (LC 10 um), 300nm (LC 20 um) e 400 nm (50 um)
- 9 iterazioni per ogni gap (0, +- 5nm, +- 10nm, +- 15nm, +- 20nm)
- Una serie con ingressi ed uscite dallo stesso lato
- Una serie di CNOT con lunghezza 20 um
- Edge coupled
- Shunt IO per l'allineamento



# Si-based single photon sources at telecom wavelengths




**Vastly unexplored research field!**

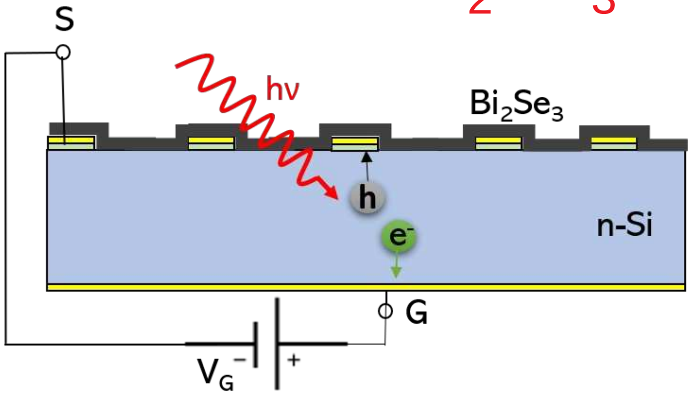
## Emitters identification

- screening of luminescent centers fabricated by ion implantation (group-IV, transition metals, halogens, He, …) at Leipzig Uni, Ruđer Bošković Inst, LNGS (LUNA), LABEC
- development of a custom telecom confocal microscope (TO)
- identification and characterization of suitable single photon emitters (TO)

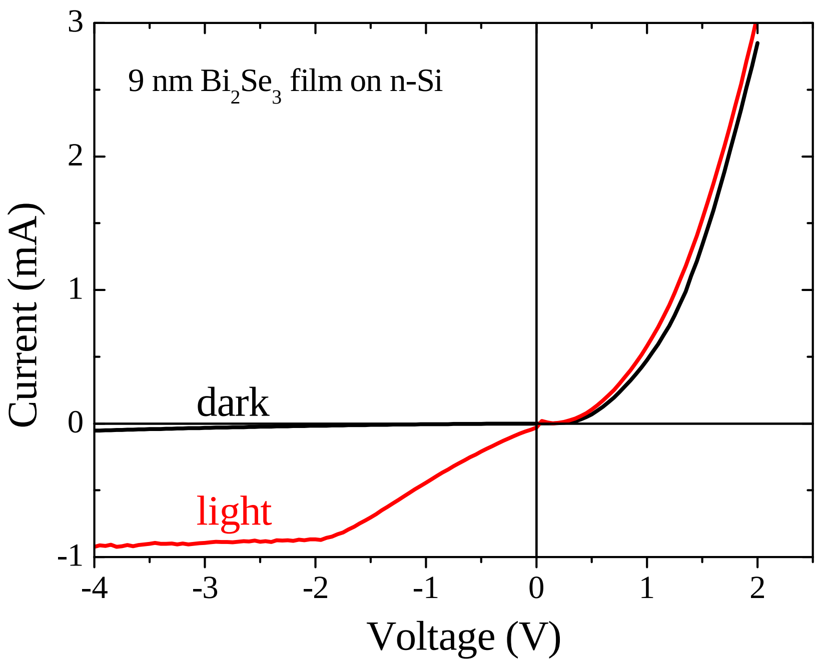
## Emitters fabrication

- ion implantation with sub-µm accuracy (collimation)
- single-ion delivery capability: the Si circuit is exploited as particle detector
- development of a custom irradiation chamber at the TO ion implanter
- exploitation of a custom irradiation chamber at the AN2000 LNL beamline

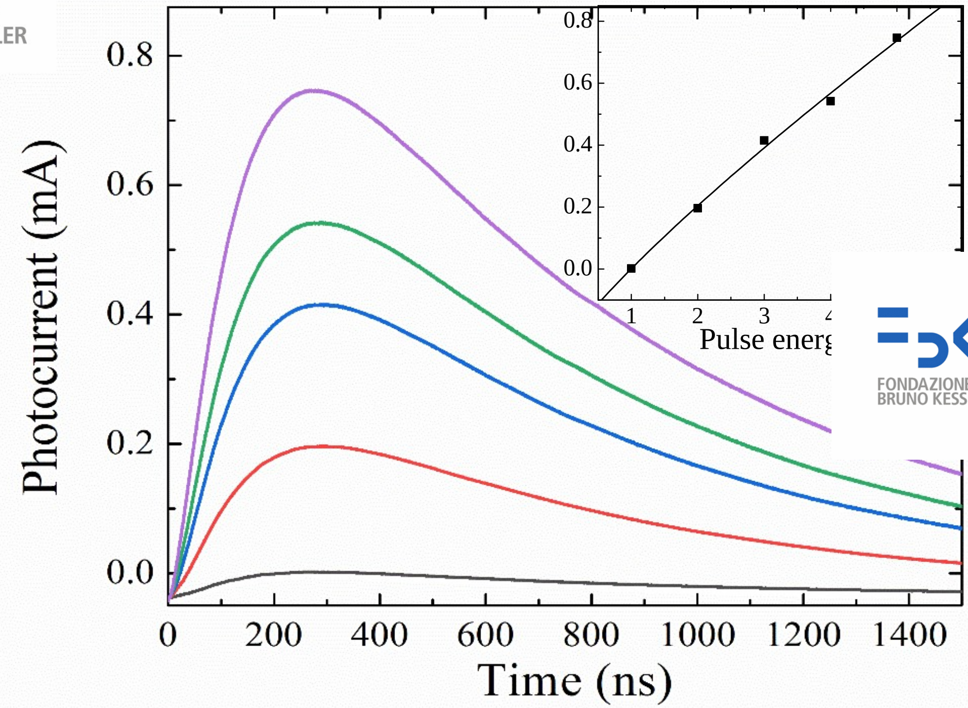
# Single Photon Detectors
# ($Bi_2Se_3$/n-Si e altri materiali 2D)




$Bi_2Se_3$ deposited on n-Si substrates shows rectification, photovoltaic response and linearity at $\lambda$ = 1550 nm




I-V characteristics of $Bi_2Se_3$/n-Si heterojunctions in dark and illuminated conditions (9 nm film).



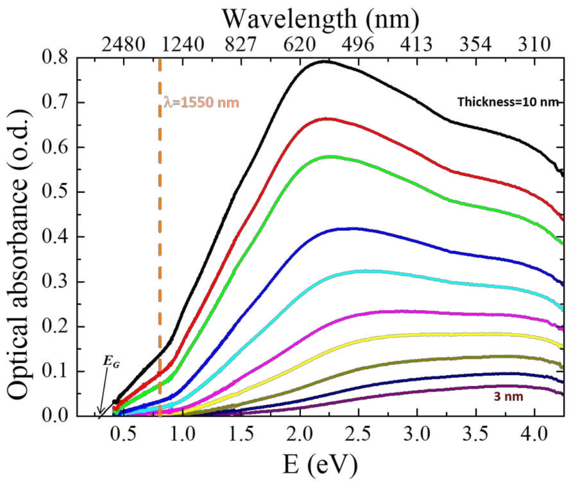

$Bi_2Se_3$/n-Si response to fs laser pulse.

Inset: photocurrent vs. laser pulse energy

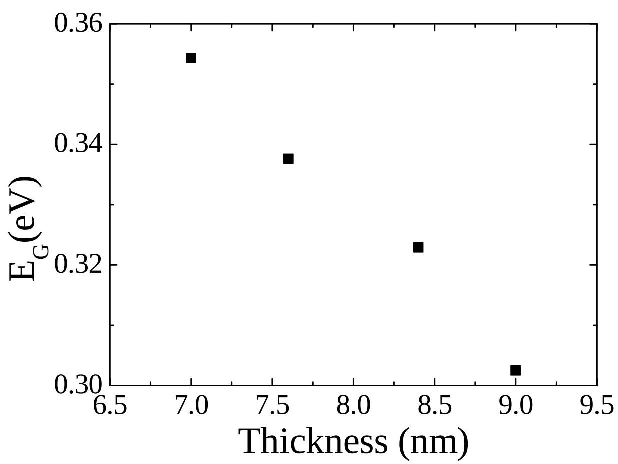
M. Salvato et al. **Nanscale DOI: 10.1039/d0nr02725a (2020).**

# Single Photon Detectors (Bi2Se3/n-Si e altri materiali 2D)

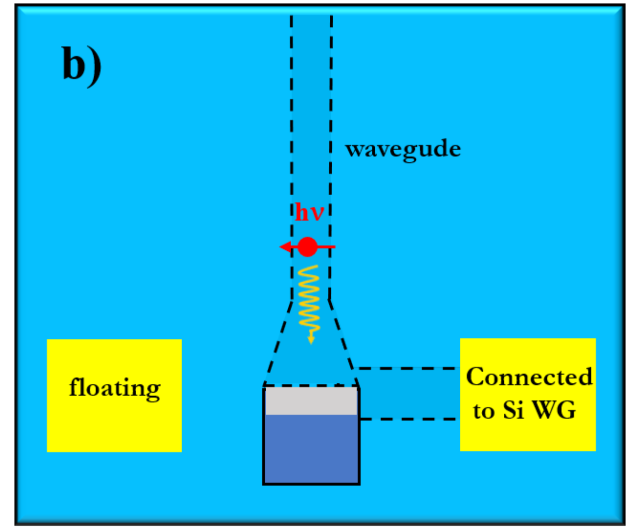
Bi2Se3 is a topological insulator (TI): insulating in the bulk and metallic on the surface

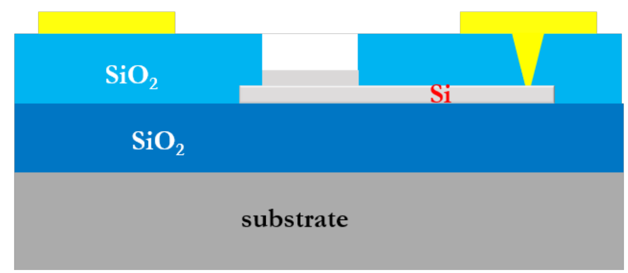


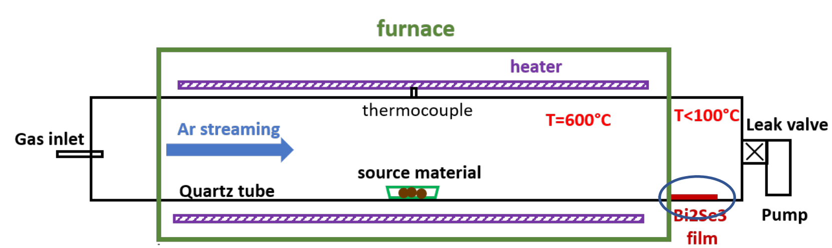

Optical absorbance at different energies with different film thickness




Bandgap vs thickness

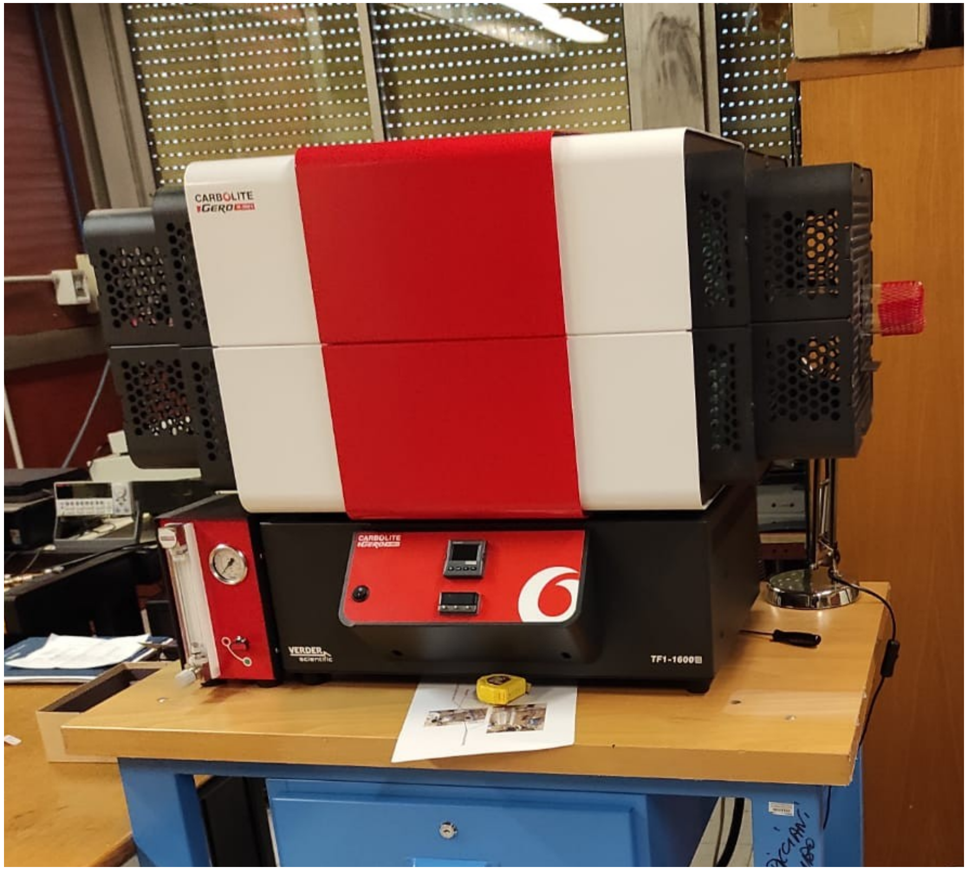


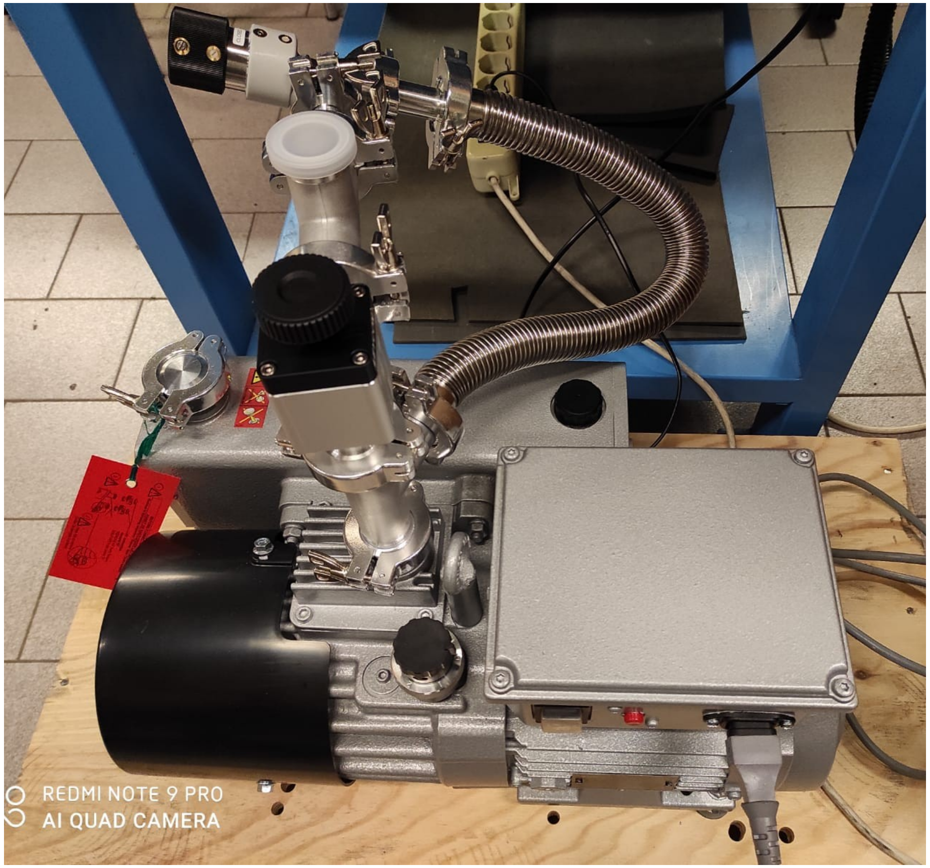




VSD furnace showing the quartz tube with source material and substrates

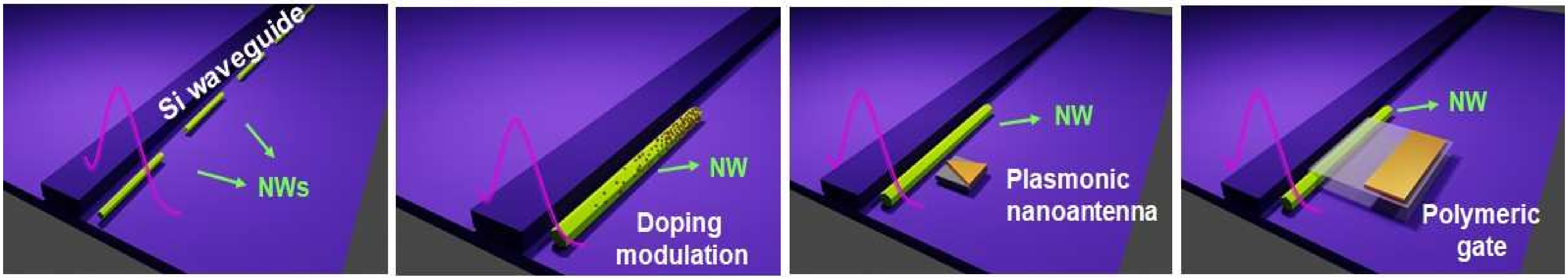
# Vapor Solid Deposition furnace



# Polarization control

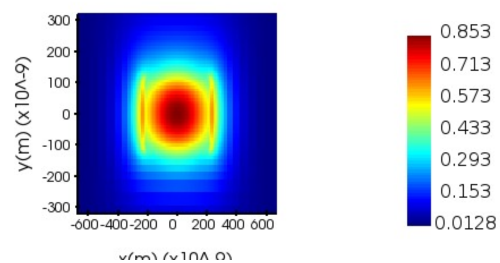
## with nanowires, graphene and other 2D materials

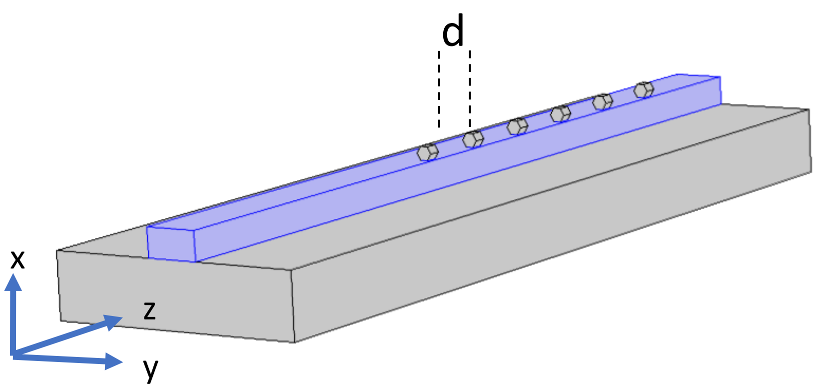



### An example: array of nanowires

- Si-wg= 450x220 nm
- NW length= 5um
- NW radius= 60nm
- Material= InP
- Number of NWs= 10
- NW separation (d) = 500nm
- TE -> TM conversion

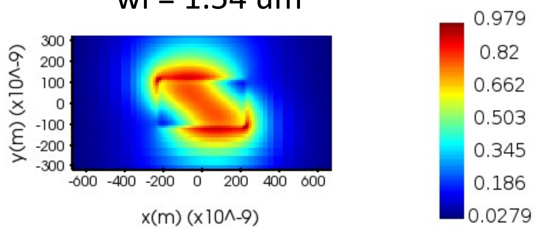
Input E-field



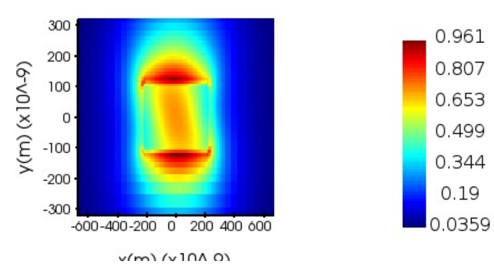




Output E-fields

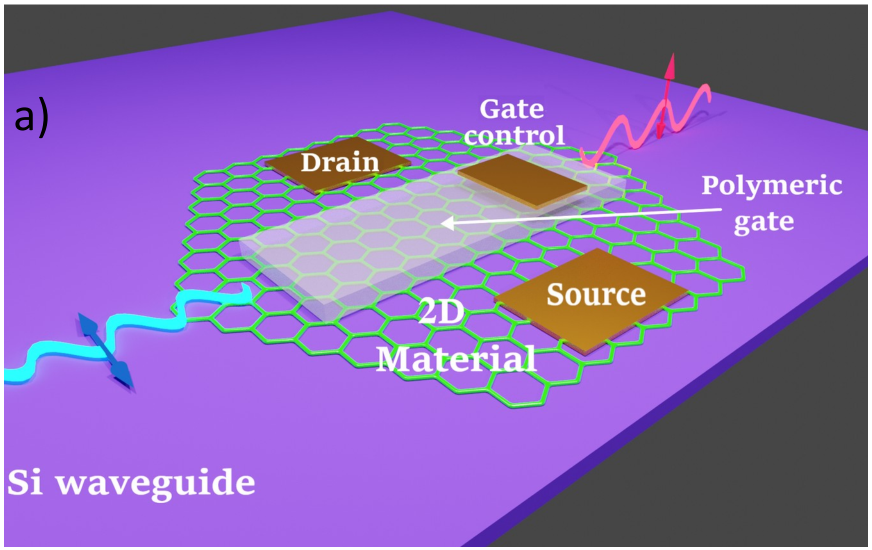
wl = 1.54 um

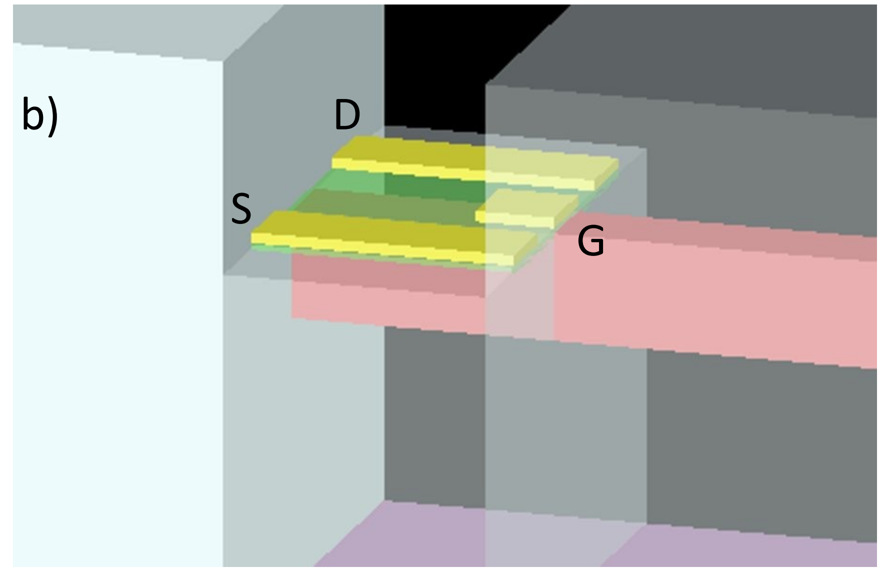


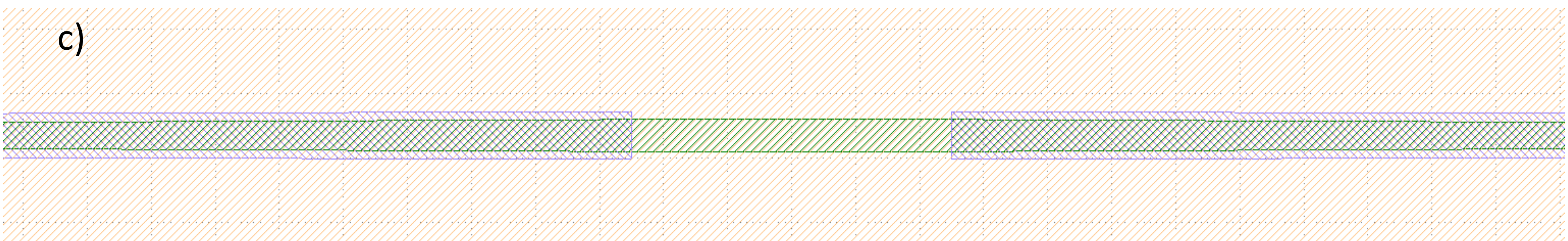

wl = 1.56 um



# 2nd PIC design (graphene)




Nano device architectures for 2D-material-based polarization processor. The nanomaterial (graphene) lies onto the Si waveguide and is coupled to it a) Schematic view, b) Perspective view from Lumerical FDTD solver, c) Zoom in view from GDSII file of the chip with the exposed region for contacting with graphene of 5 × 50 µm.

# Funding requests

La stazione di test (generatore di fotoni entangled, rivelatore di singolo fotone, tavolo ottico, movimenti, strumentazione varia) è arrivata (o arriverà a brevissimo).
Per il 2023 chiediamo:

INV 8 kEuro Scientific workstation
INV 4 kEuro V-groove coupling
CON 6 kEuro Laboratory consumables
MIS 5 kEuro travels

# Personale

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Bonaiuto | Vincenzo | ROMA2 | G1 | Associato | Tecnologica Ricercatori/Professori università | Attivo | CSN1 | 30% |
| Dao | Thu Ha | ROMA2 | G2 | Associato | Tecnologica Dottorandi | Attivo | CSN5 | 100% |
| De Matteis | Fabio | ROMA2 | G1 | Associato | Tecnologica Ricercatori/Professori università | Attivo | CSN5 | 80% |
| Francini | Roberto | ROMA2 | G1 | Associato | Scientifica Ricercatori/Professori università | Attivo | CSN5 | 40% |
| Marin | Cosmin | ROMA2 | G1 | Associato | Scientifica Laureandi Magistrali | Attivo | CSN5 | 100% |
| Prosposito | Paolo | ROMA2 | G1 | Associato | Tecnologica Ricercatori/Professori università | Attivo | CSN2 | 60% |
| Salamon | Andrea | ROMA2 | G1 | Dipendente | Ricercatore | Attivo | CSN5 | 25% |
| Salvato | Matteo | ROMA2 | G1 | Associato | Scientifica Ricercatori/Professori università | Attivo | CSN5 | 90% |
| Sargeni | Fausto | ROMA2 | G1 | Associato | Tecnologica Ricercatori/Professori università | Attivo | CSN1 | 20% |

# UNIDET

## Universal detector for quantum light

Andrea Salamon

22/07/2022

# The team

Andrea Salamon 0.4 FTE
Thu Ha Dao 0.2 FTE

Trento Institute for Fundamental Physics and Applications

0.5 FTE Mirko Lobino
0.3 FTE Paolo Rech
0.2 FTE Alberto Quaranta

Francesco Mattioli 0.2 FTE
Alessandro Gaggero 0.2 FTE
Francesco Martini 0.2 FTE

FONDAZIONE BRUNO KESSLER

Martino Bernard 0.2 FTE

# Aim of the experiment

- Fabricate a detector that can be integrated with waveguide
- **Photon number resolving** detection
- Use a platform that is good for quantum photonics
- Complement the research done in **QUANTEP**

# Superconducting single photon detectors

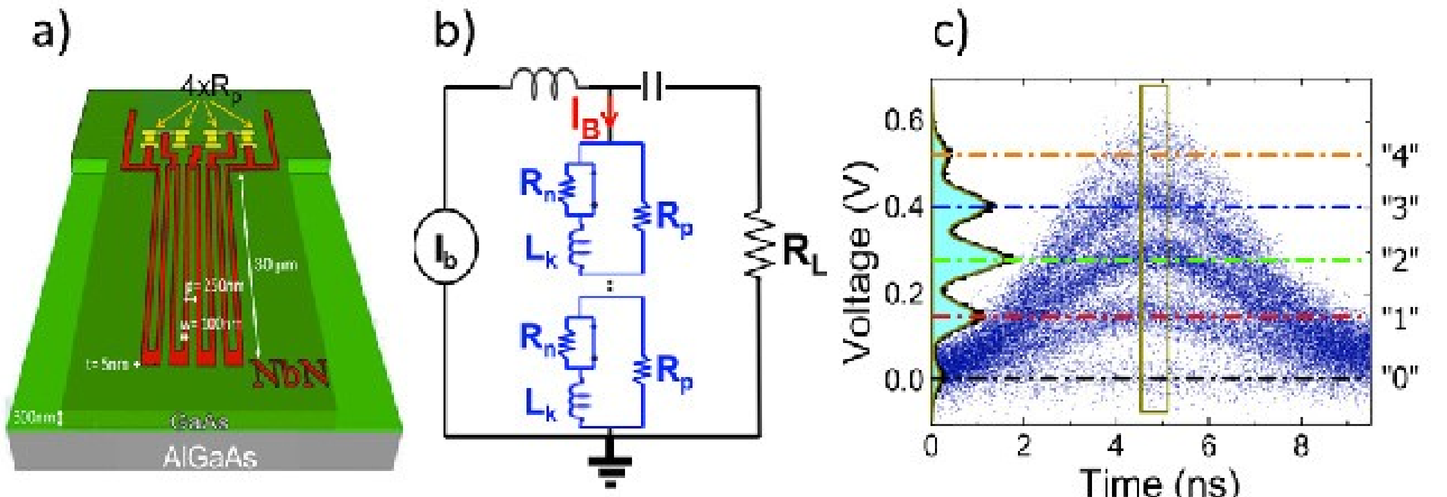



**Figure 1** a) Schematic of a multiplexed photon number resolving detector integrated on a ridge GaAs waveguide, developed using a series connection of four pixel SNSPD and b) its equivalent electric circuit, which includes the amplifier input impedance $R_L$. c) Pulse height corresponding to the number of absorbed photons [25].

# Thin-Film Lithium Niobate

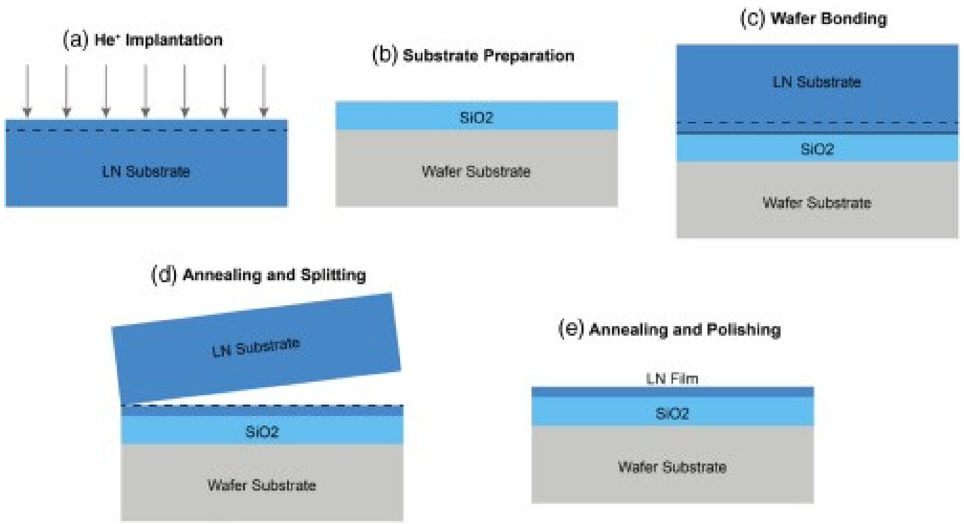
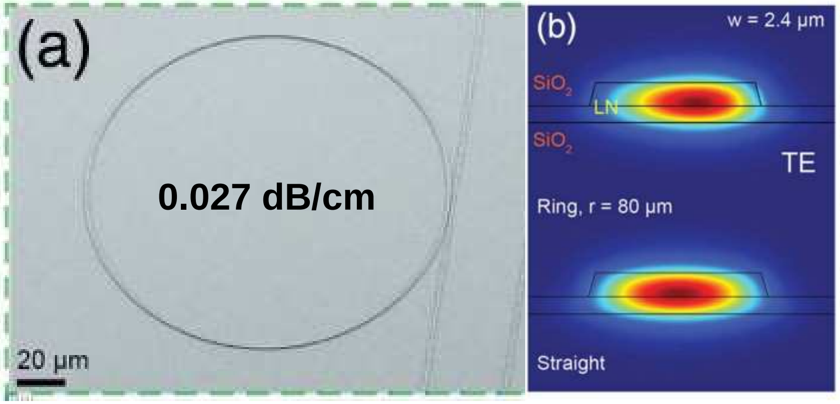



Image from: Di Zhu *et al.*, *Adv. Opt. Photonics, Vol. 13, Issue 2, pp. 242-352,* Jun. 2021

Image from: M. Zhang, C. Wang, R. Cheng, A. Shams-Ansari, and M. Loncar, *Optica*, vol. 4, no. 12, Aug. 2017




Apply Resist | Pattern Resist to Form Mask | Etch Substrate | Remove Mask

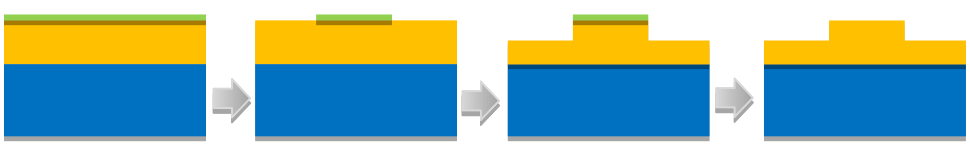
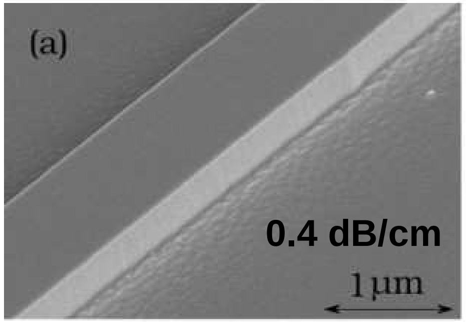
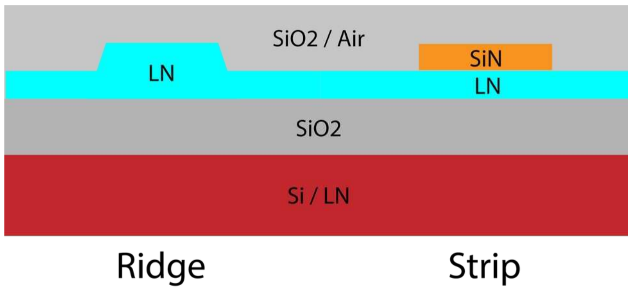


Image from:
I. Krasnokutska, J.-L. J. Tambasco, X. Li, and A. Peruzzo, *Opt. Express*, vol. 26, no. 2, p. 897, Jan. 2018



# TFLN Strip Loaded Waveguides



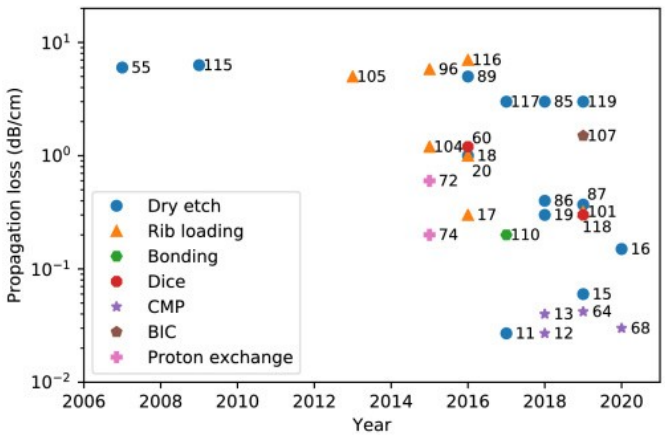




Image from: Di Zhu *et al.*, *Adv. Opt. Photonics, Vol. 13, Issue 2, pp. 242-352,* Jun. 2021

| | Ridge | | Strip |
|---|---|---|---|
| + | High mode confinement (typically <1um²) | + | Nonlinear conversion efficiency (1000-4000% /Wcm²) |
| + | Small bending radius (<100um) | + | Nonlinear phase matching more tolerable to fabrication errors |
| + | nonlinear conversion efficiency (4000 - 7000% /Wcm²) | + | Fabrication of SiN well established |
| + | Less susceptible to lateral leakage | + | Domain inversion for periodic poling can be done pre or post waveguide fabrication |
| + | Ultra-low propagation loss (3dB/m @1550nm) [1] | + | Low propagation loss (0.2dB/cm @ 1550nm) [2] |
| – | Nonlinear phase matching highly susceptible to fabrication errors | – | Larger bending radius (>300um²) |
| – | Fabrication of ultra-low loss waveguides difficult in practice | – | Shorter wavelengths prone to lateral leakage |
| – | Domain inversion prior to etching introduces additional losses due to differential etch rates between domains leading to increased losses and reduce efficiencies | | |


[1] M. Zhang, C. Wang, R. Cheng, A. Shams-Ansari, and M. Lončar, *Optica*, vol. 4, no. 12, p. 1536, Dec. 2017.
[2] A. N. R. Ahmed, S. Shi, M. Zablocki, P. Yao, and D. W. Prather, *Opt. Lett.*, vol. 44, no. 3, p. 618, Feb. 2019.

# Superconducting single photon detectors

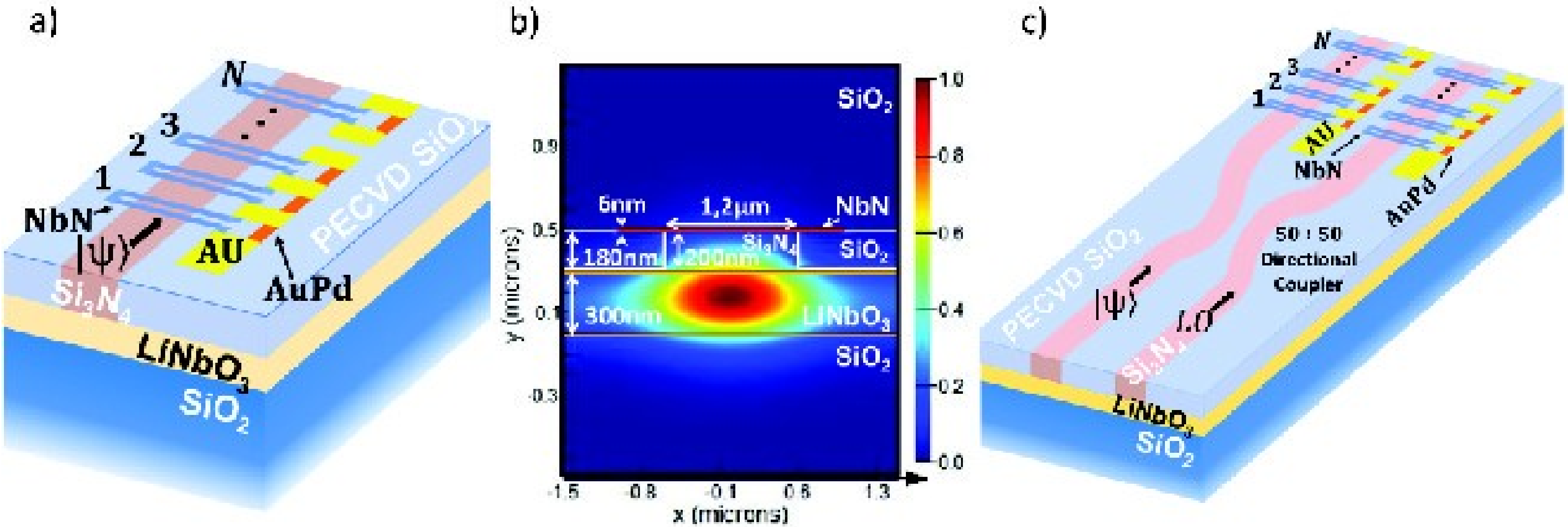



**Figure 2** a) Schematic of the integrated PNR to develop in this project showing a series of N pixels composed by a NbN nanowire (80 nm width) and an AuPd on-chip parallel resistance (Rp=20 Ω value). b) Field intensity for the first TE mode propagating in the waveguide where the light absorption in each NbN nanowire element is at 3.4%. c) Schematic of the hybrid detector.

# Funding requests

| | | | | |
|---|---|---|---|---|
| RM2 | Equip | 15 | | Nexus isolated optical table with accessories at INFN Tor Vergata |
| | Equip | 29 | | IR microscope (InGaAs camera, objective, translation stage) at INFN Tor Vergata |
| | Equip | 8 | | Stabilized free-space IR light source with translation stage, adapter and filter at INFN Tor Vergata |
| | Cons | 4 | 4 | Fiber array holders and v-groove arrays with spot size converters ar INFN Tor Vergata |
| | Cons | 5 | 5 | Laboratory consumables (PCB, glue, fibers, cables) for characterization and packaging at INFN Tor Vergata |
| | Cons | 6 | | SEM filament replacement at CNR-IFN |
| | Cons | 10 | | EBL filament replacement at CNR-IFN |
| | Cons | 10 | 10 | EBL usage (200 Euro/h, 50 h/year) at CNR-IFN |
| | Cons | 9 | 9 | Cleanroom consumables (resist, metals, …) at CNR-IFN |
| | Cons | 3 | 3 | Laboratory consumables (electrical and optical) at CNR-IFN |
| | Trav | 10 | 10 | Collaboration and common tests |
| TIFPA | Equip | 80 | | Cryostat for detector characterization at TIFPA |
| | Cons | 10 | 10 | Equivalent masks (2.5 kEuro/mask, 4 masks/year) according to INFN-FBK agreement |
| | Cons | 20 | 20 | Cleanroom and consumables costs for waveguide fabrication at FBK |
| | Trav | 10 | 10 | Collaboration and common tests |
| TOT | | 229 | 81 | |