# Photon Number-Resolving Detectors for Integrated Quantum Sensing

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# Presentation Overview

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**Available technologies:** ⟶ Current state of PNRDs
⟶ Our approach: SNSPDs for PNRD
⟶ Why lithium niobate?

**Desing and simulations:** ⟶ Detector architecture
⟶ FEM Simulations
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**Conclusions and Q&A**

# Introduction

Photon number resolving detectors (PNRDs)

How many photons are here?

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## Photon number resolving detectors (PNRDs)

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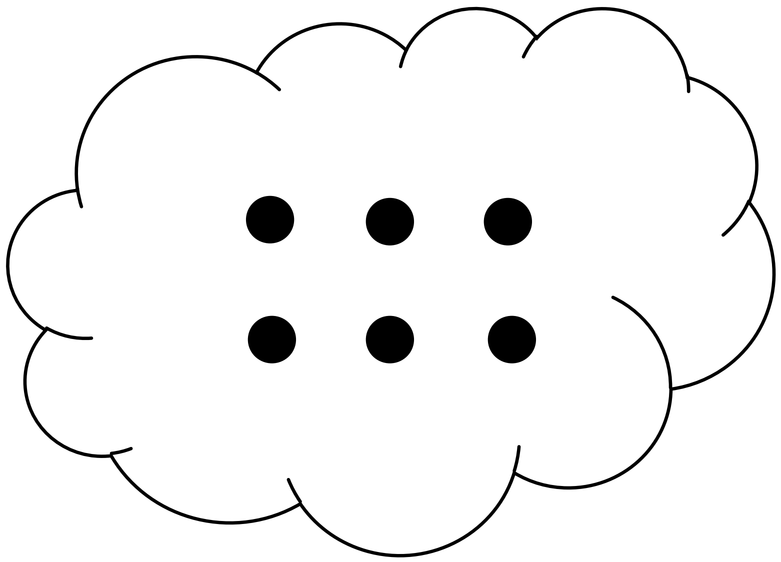


$m = 6$ photons

# Available Technologies

## Current state of PNRDs

**Transition Edge Sensors (TES)**:

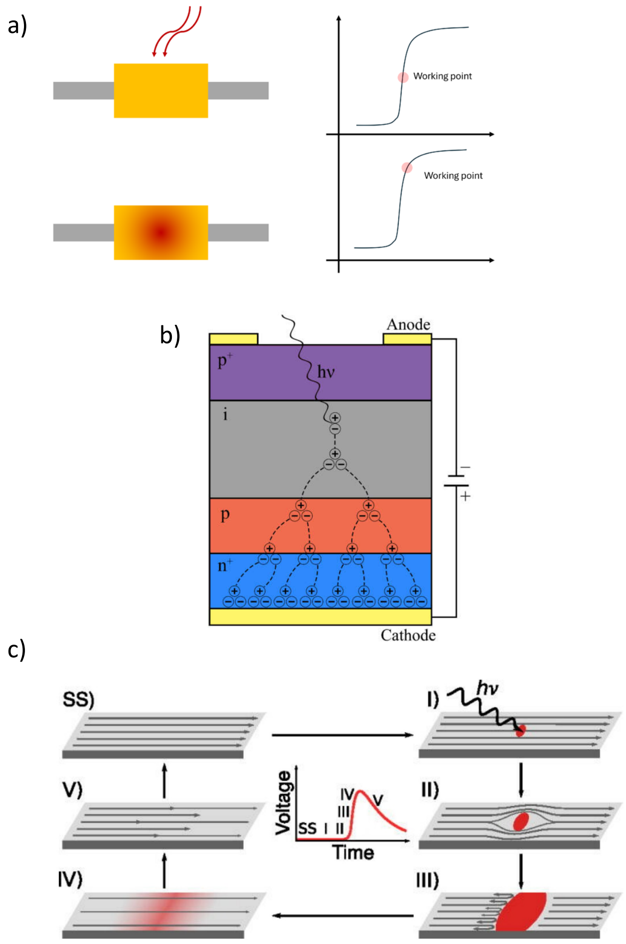
- Pro: high quantum efficiency (~98%) and few photon-number resolution
- Con: very low working temperatures (few mK) and slow response time (1us)

**Avalanche PhotoDiodes (APD)**:

- Pro: no needing of cryogenic temperature and high sensitivity
- Con: lower quantum efficiency (>50%) and high noise

**Superconducting Nanowires Single-Photon Detectors (SNSPD)**:

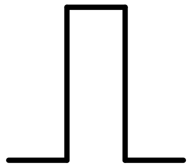
- Pro: high quantum efficiency (80-95%), low dark counts rates (mHz) and low response time (<10ps)
- Con: single-photon resolution and needing of low temperatures (few K).



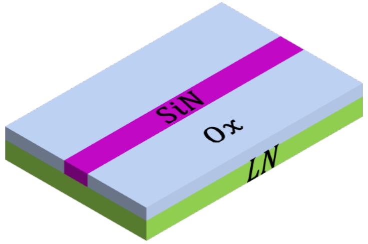

a) M. De Lucia *et al.*, *Instruments* **2024**, *8*(4), 47
b) K. A. Lozovoy *et al.*, *Nanomaterials* **2023**, *13*(23), 3078
c) J. A. Sutton's Master Thesis, Aalto University of Electrical Engineering

# Available Technologies

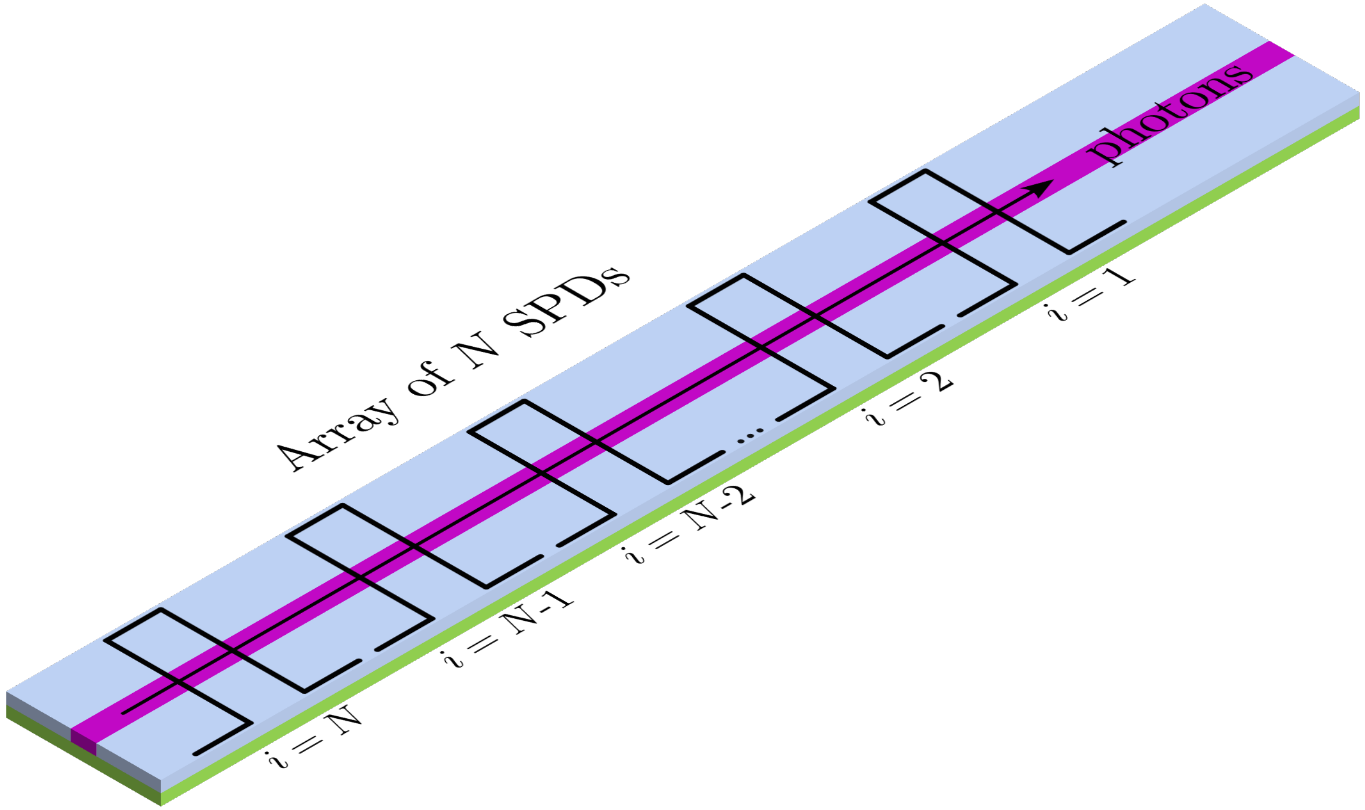
Our approach: integrated SNSPDs for PNRD



Niobium Nitride (NbN)
SNSPD




Silicon Nitride (SiN) strip-loaded
Lithium Niobate (LN) waveguide

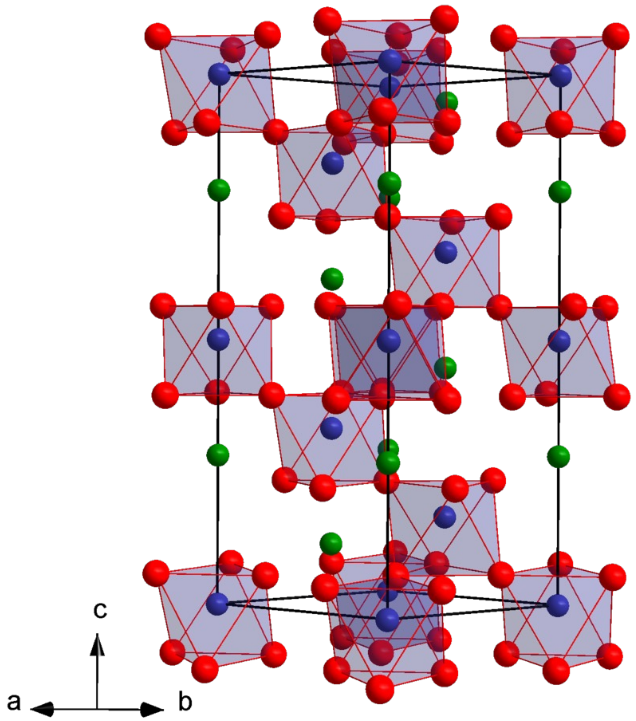


# Available Technologies

## Why Lithium Niobate?

- Negative uniaxial birefringent material (i.e., $n_e < n_o$) with $n_o \sim 2.21$ , $n_e \sim 2.14$ at 1550 nm
- Transparent for wavelengths between 0.4 µm (blue) and 5 µm (mid-infrared)
- Can be adopted for optical waveguides, optical modulators and various other linear and non-linear optical applications.

Trigonal structure†

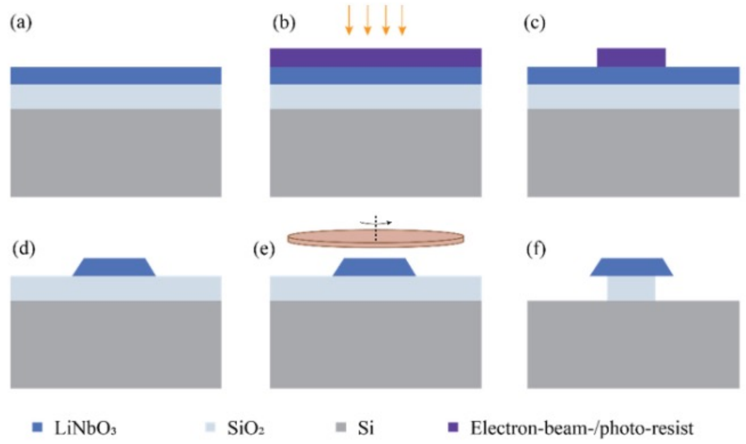



**Ref:** Xiao Y. *et al.*, "Ultra-high-Q Optical Microcavities", World Scientific (2020); †Picture from https://en.wikipedia.org/wiki/Lithium_niobate

# Available Technologies

## Why Lithium Niobate?

### Direct dry-etching (DE)



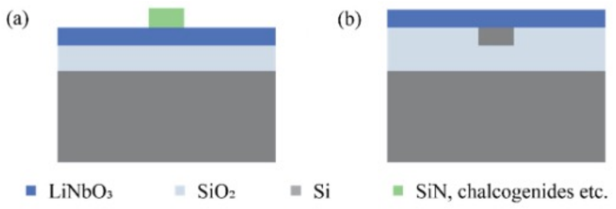

Pros:

- Waveguides made totally of $LiNb0_3$

Cons:

- Difficult fabrication technique
- Non-vertical or non-smooth walls

### Heterogeneous integration (HI)




Pros:

- Exploits mature fabrication techniques.
- $LiNbO_3$ is kept etchless

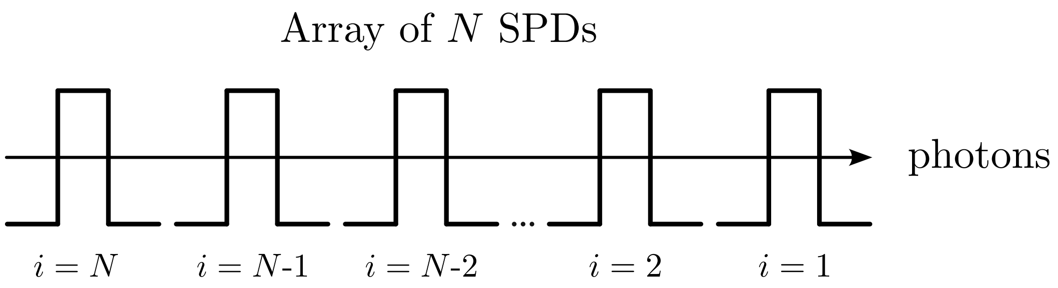
Cons:

- Quality factors still less than dry-etching or mechanical polishing fabrications.

**Ref:** Xiao Y. *et al.*, "Ultra-high-Q Optical Microcavities", World Scientific (2020)

# Design and Simulations

## Linear multiplexing of SNSPDs




$$\boxed{p_i = \frac{1}{N}} \iff \boxed{\eta_i = \frac{1}{i} \; \forall i \in [1, N]} \quad (\star)$$

Hypothesis $(\star)$ implies that, given $m$ photons to be number-resolved, the fidelity of the system is equivalent to evaluate the probability of disposing $m$ balls inside $N$ boxes, with at most 1 ball per box.

$$\Downarrow$$

$$\boxed{F = m! \cdot \binom{N}{m} \cdot \frac{1}{N^m}}$$

Multiplicity factor

Ways of distributing $m$ balls in $N$ boxes

Probability of measuring $m$ photons

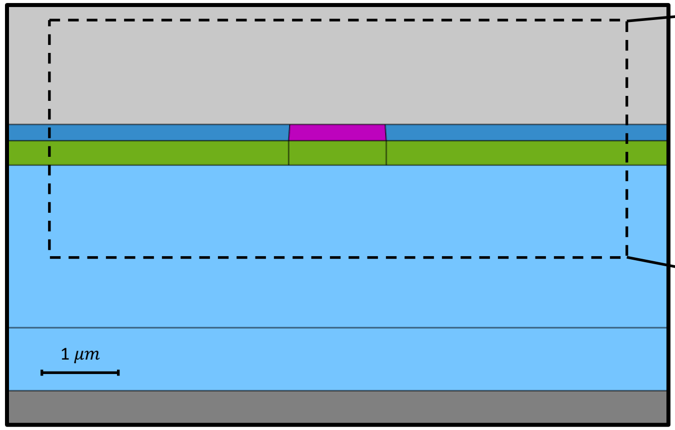
# Design and Simulations

## FEM Simulations: free propagation

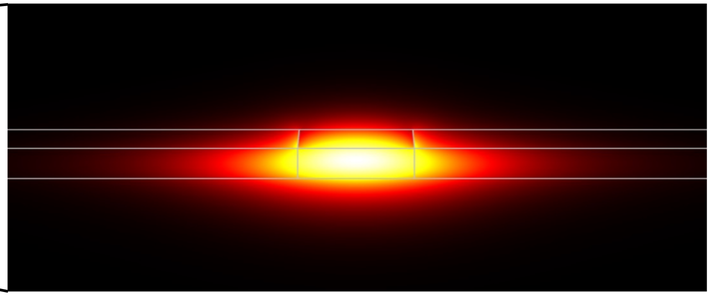
### List of parameters

| $\lambda = 1.55\ \mu m$ | $SiO_2$ | $LiNbO_3$ | $Si_3N_4$ | NbN |
|---|---|---|---|---|
| Refractive index $n$ | 1.44 | 2.21($o$)<br>2.14($e$) | 1.88 | 5.23+<br>$i$5.82 |
| Thickness $h$ ($\mu$m) | 3.00 | 0.3 | 0.2 | 0.006 |
| Width ($\mu$m) | slab | slab | 1.20 | 0.08 |

### Cross section of the waveguide




### Strip-loaded mode

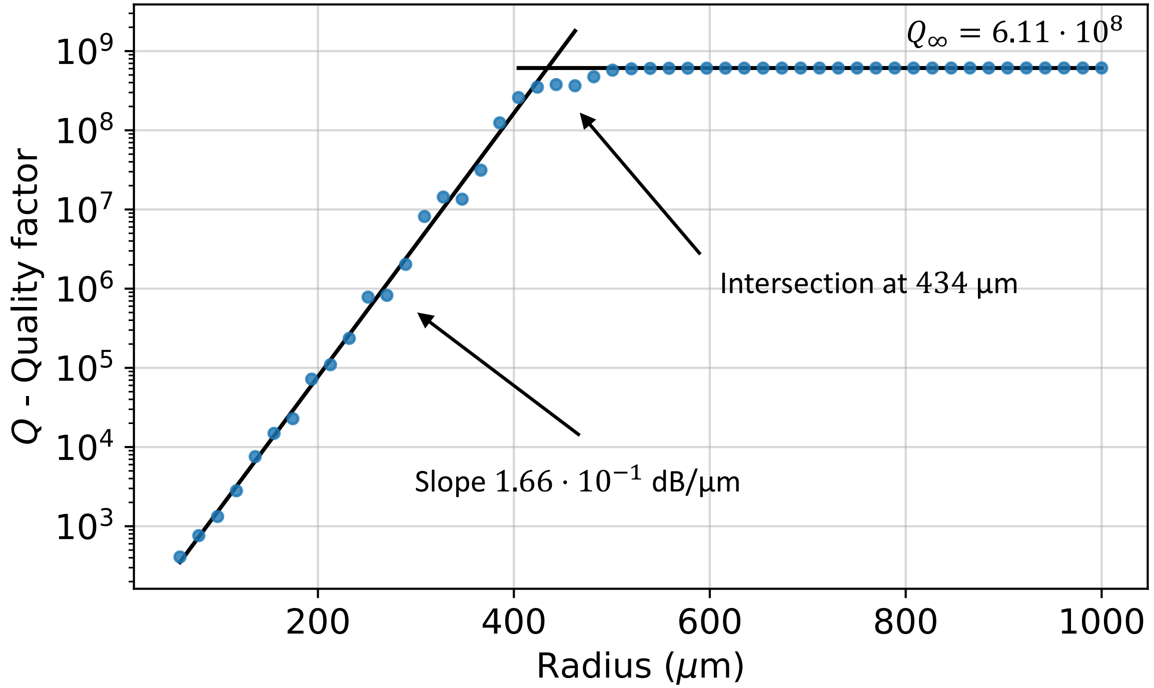


Material colors: Air, Silicon Nitride, Oxide, Oxide, Lithium Niobate, C-Silicon

**Ref:** Limongi L. *et al.*, Optics Communications **575**, 131244 (2025)

# Design and Simulations

## FEM Simulations: bends

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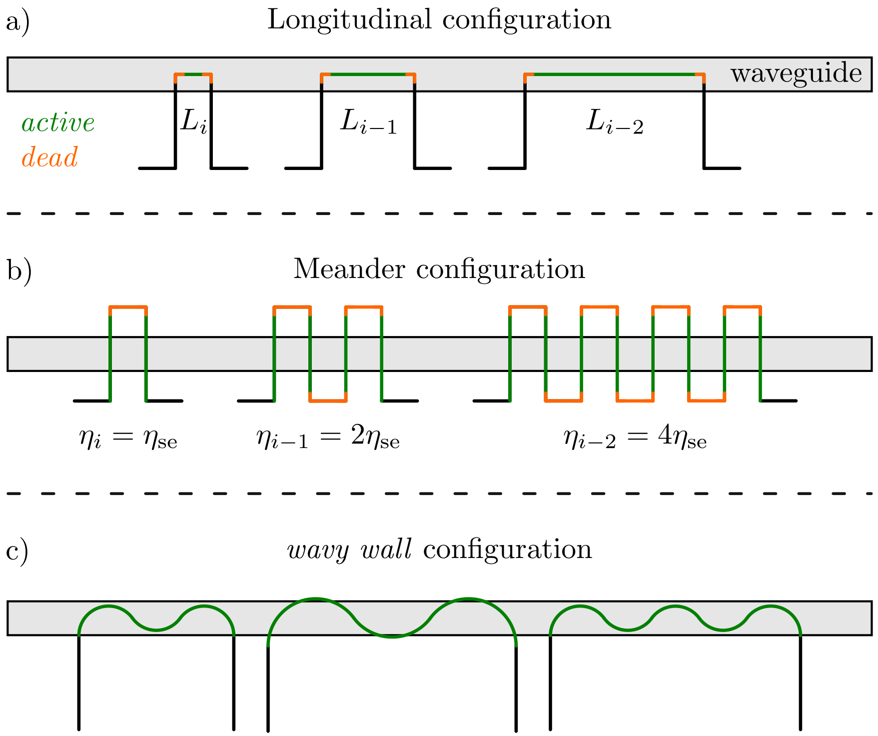
# Design and Simulations

## Desing challenges and solutions




Pro: continuously tunable absorption

Con: 90° bend (dead) on top of the waveguide

Pro: 90° bend (dead) away from the waveguide

Con: discretization of the absorption

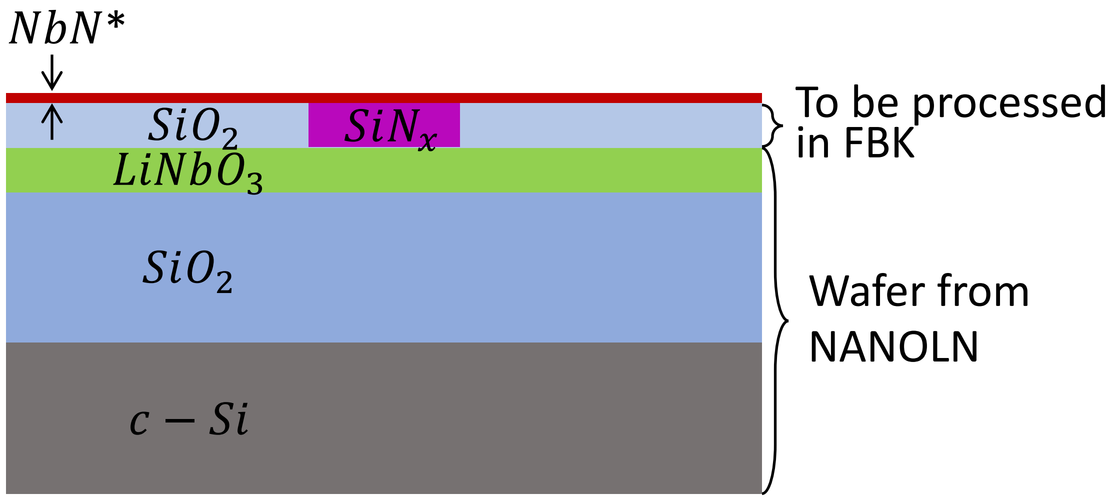
Pro: Only active nanowire, continuously tunable absorption

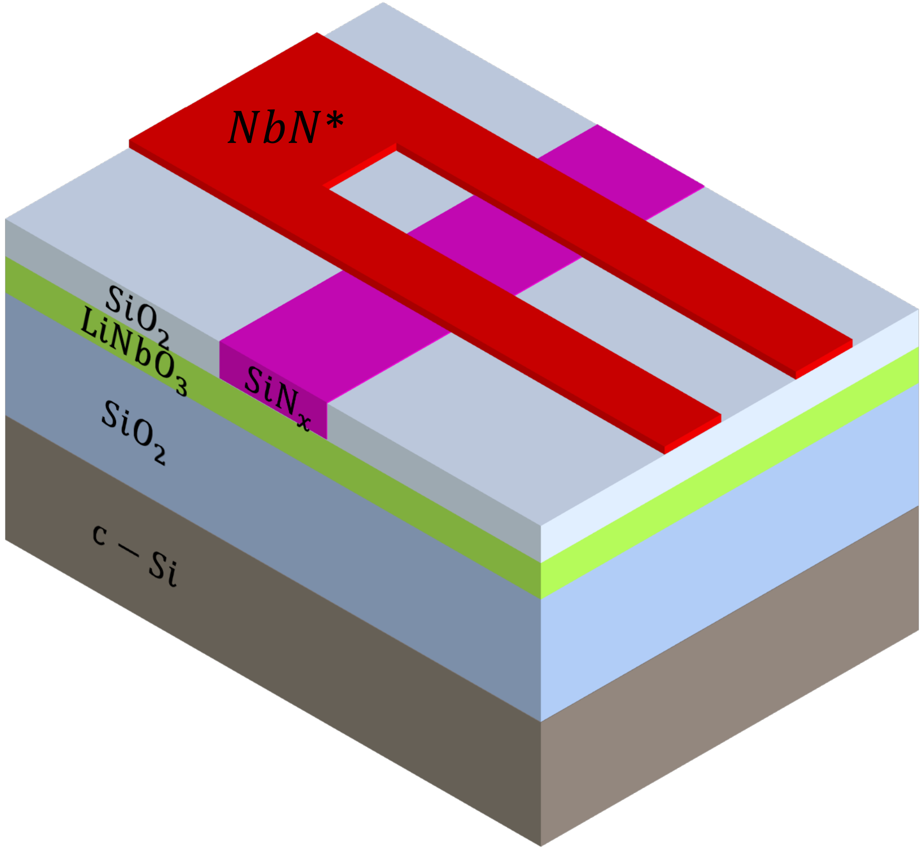
Con: Very challenging fabrication

**Ref:** Limongi L. *et al.*, Optics Communications **575**, 131244 (2025)

# Implementation and Future Perspectives

## Fabrication of the device




**Not to scale**; ***Fabrication at CNR-IFN facilty, Rome**

# Conclusions and Q&A

## Summary and takeaways

- **PNRDs are pivotal for quantum sensing**, with various available technologies.
- **SNSPDs integrated on lithium niobate offer a promising alternative**, combining high efficiency with photonic integration
- **Technological challenges remain** (e.g., complex fabrication, efficiency optimization), but recent advancements open new possibilities.
- **Next steps**: device fabrication and experimentally test its performance.