GRAFIQO (Preventivi 2026)

GRAvitational Force In Quantum Optomechanics

CSN2- Started January1 2023; 6 years

Objectives: explore the territory between quantum physics and gravity. More specifically

1. **Measurement of the gravitational force produced by the smallest source mass (masses ~ 10 mg)**

2. **Measurement of this small force when the test mass oscillator is in a quantum state (limited only by quantum fluctuations)**

Responsabile nazionale: **Francesco Marin**

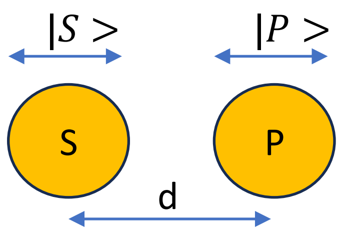
Unità INFN partecipanti: **Trento, Firenze, Perugia**

Responsabili locali: **Enrico Serra (TN) , David Vitali (PG)**

Physics & Motivation

Are we sure that the gravity must be quantized?
We can answer even without any clue about quantum gravity (i.e. in a model-independent way):

Gravitational entaglement ?



Phase shift of a QG signal

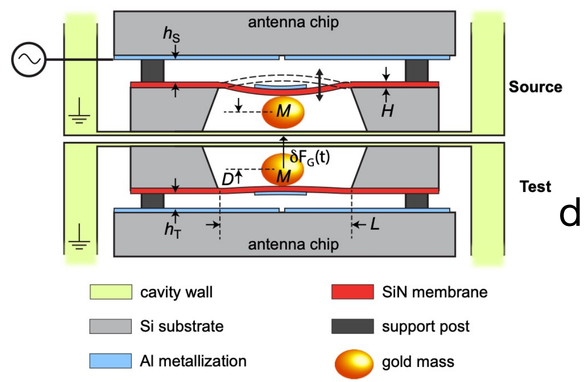
$$\phi_g = G\frac{m_s m_p}{\hbar d}t$$

We need large masses isolated from noise and that decohere after a long lime.

Feynmann 1957 The Chapel Hill Conference

Out of the current technology !

An intermediate step is possible: accurate measurement of the gravitational force between objects in quantum states i.e quantum-limited position-momentum fluctuations



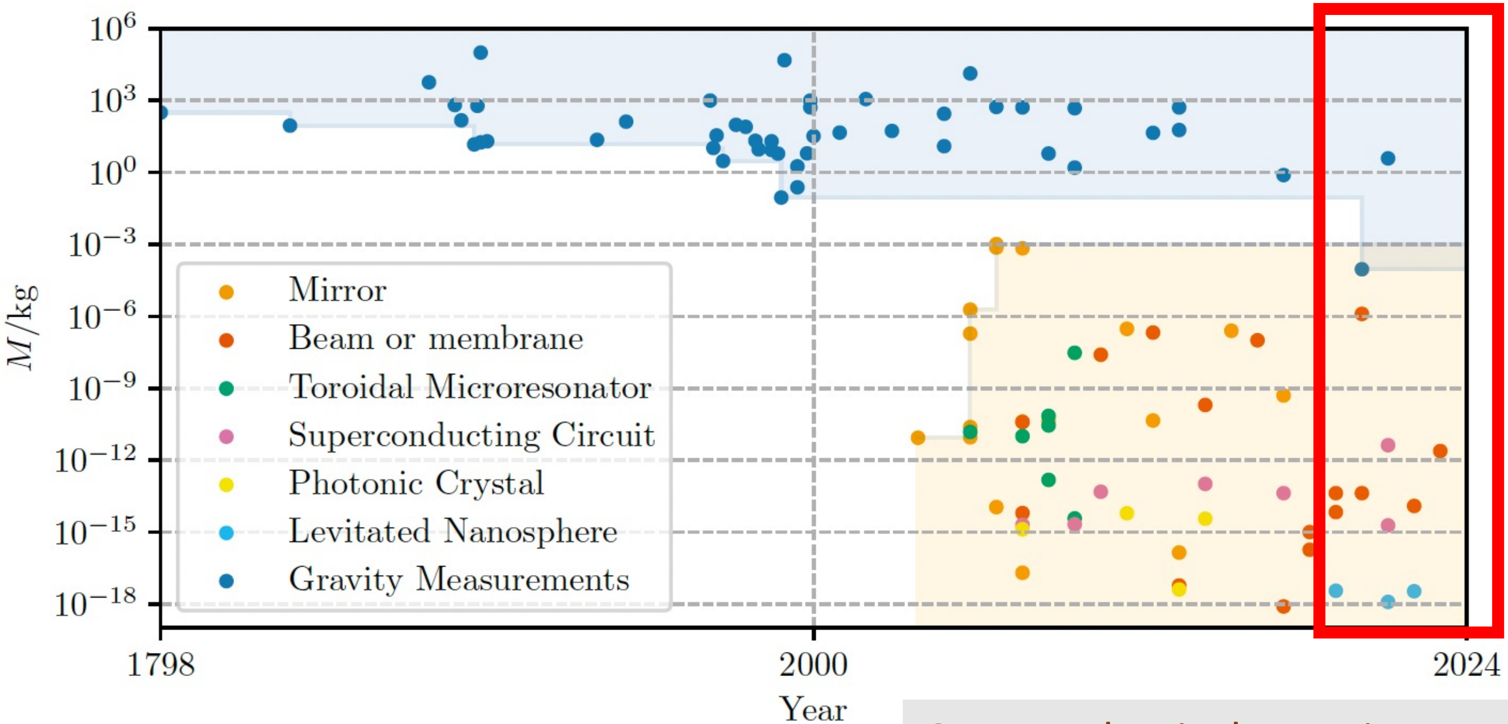
Microwave operated MEMS system in a dilution cryostat at 10 mK

M. A. Sillampää Phys. Rev. Applied 15, 034004 2021

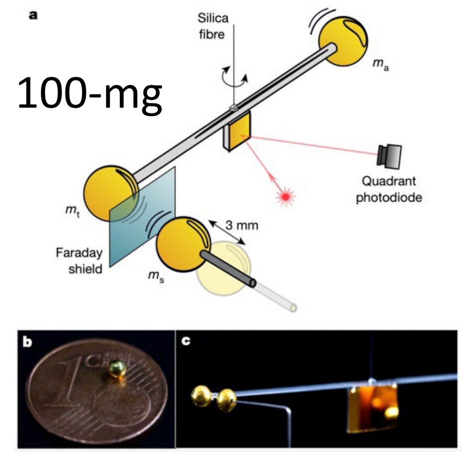
We use an alternative approach based on **optomechanics** (interaction between photon-phonon) !!

Optomechanics & gravity

Gravity experiments



100-mg



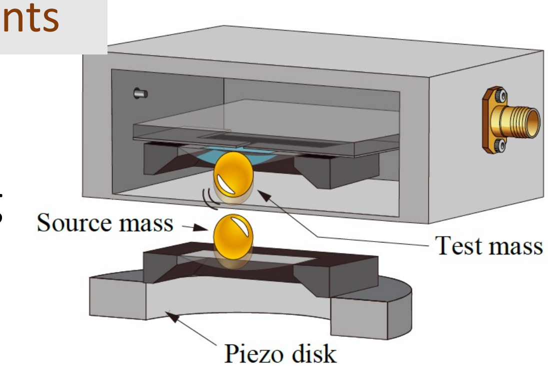
Torsional pendulum
(interaction between two gold spheres)

Optomechanical experiments

REF. Cavity Optomechanical Probe of Gravity Between Massive Mechanical Oscillators
Tang et al. 2025

OMIT detection

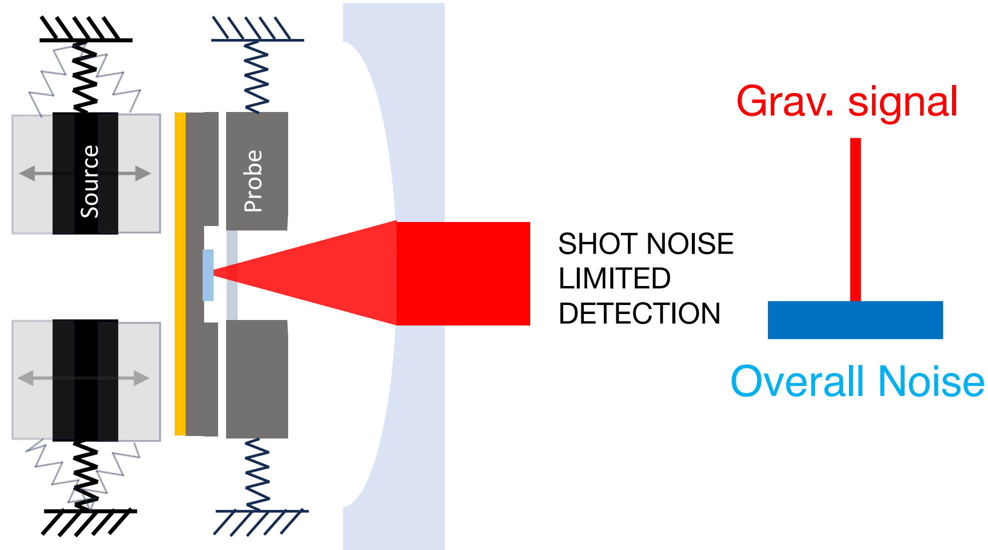
$M_1 = M_2 = 1.26$ mg



GRAFIQO experimental set-up

Mixing chamber of a dilution cryostat @ T=20 mK

Observe the **gravitational signal** produced by the oscillation of a source mass when the test mass is in **a non-classical state**



Gravitational gradient $\propto 10^{-12}$ N/m

$f_{source} = f_{Probe} = 20$ KHz $\qquad M_{source} = M_{Probe} = 14.9$ mg

Objective: measure the gravitational signal emerging from the thermal noise floor produced by the source mass and read out optically with a probe mass. We also cool down one or both masses to the ground state. A membrane is dispersive coupled (or '**membrane** in the middle') to a high-finesse Fabry-Perot optomechanical.

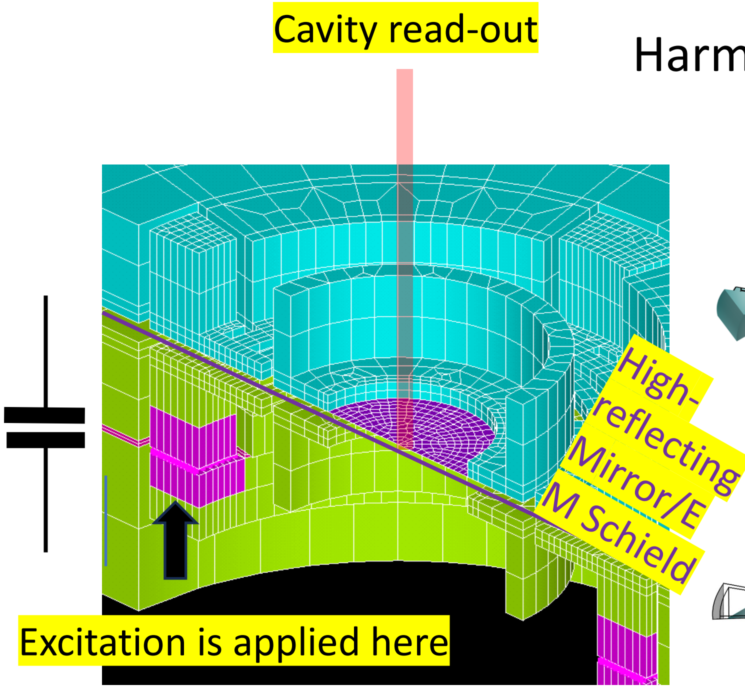
Major issues in the exp.

- Technical noises (electronic, laser noise)
- **Reducing thermal noise of the resonators** (development of a high-Q resonator couple)
- **Reducing Cross-talk between the resonators** (proper resonator & optical cavity design)
- Set up advanced optical protocols for cooling
- **Preventing electrostatic spurious signals** that can mask the gravitational signal (electrical shield)
- **Reducing Environmental vibrational noise** in a dilution cryostat
- Reaching the sub-K temperature. Target 20 mK with **no stress induced by thermal expansion coefficients** (proper resonator & optical cavity design).

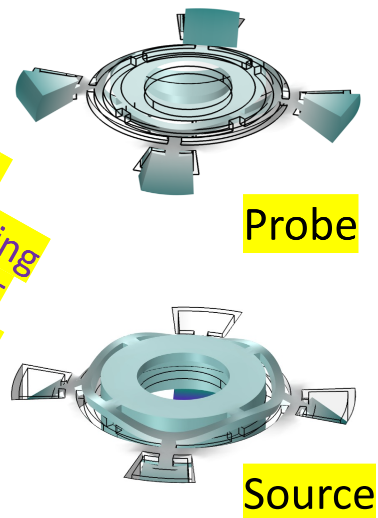
Tasks and operations overseen by TIFPA

Silicon MEMS oscillators for GRAFIQO

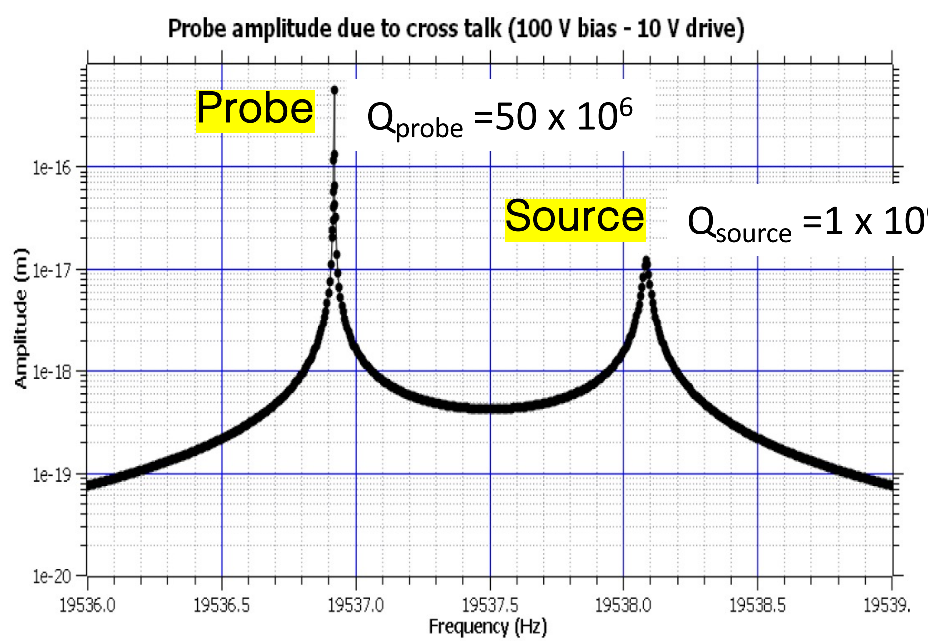
TIFPA- Activity 2024-2025 WP1 - T1.1 del CDR



Harmonic vibration of resonators.



High-Q silicon resonators are needed at low temperatures

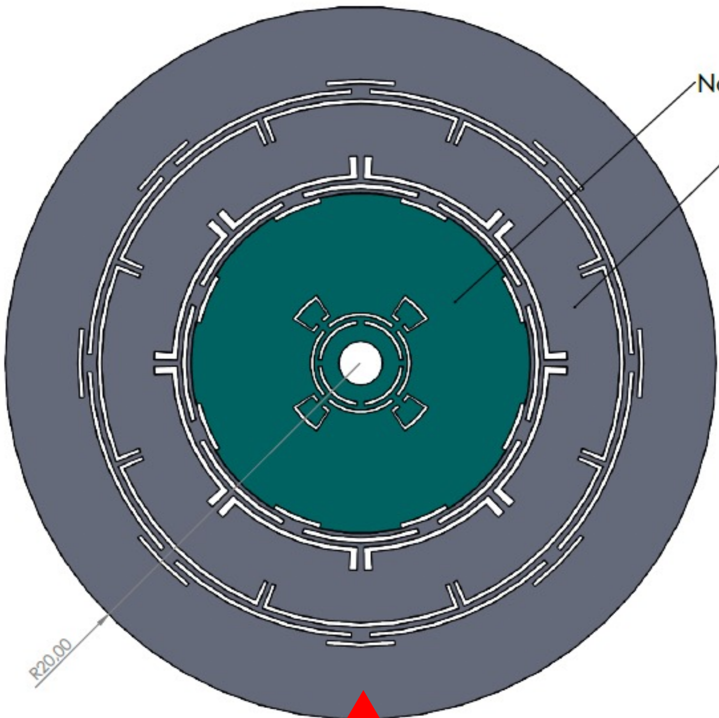


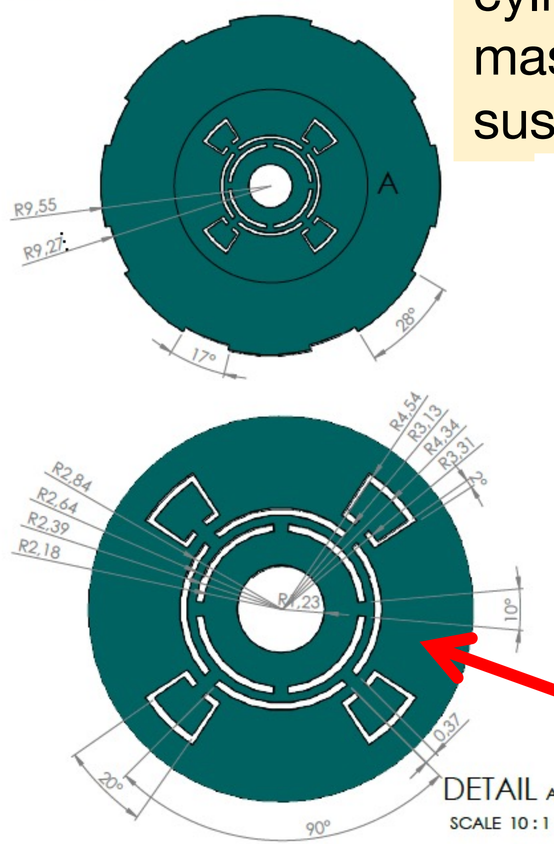
The source oscillator is excited internally and resonantly within a bandwidth of 1 Hz to achieve at least 1 µm of amplitude from the source resonator

Development of the design concepts

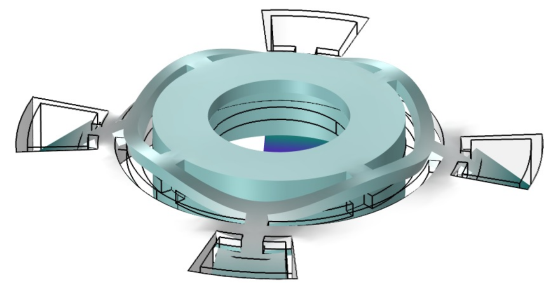
TIFPA- Activity 2024-2025

SOURCE RESONATOR - Nodal part front side





1- Balance the recoil of the cylinder mode with four masses to realise a nodal suspension.

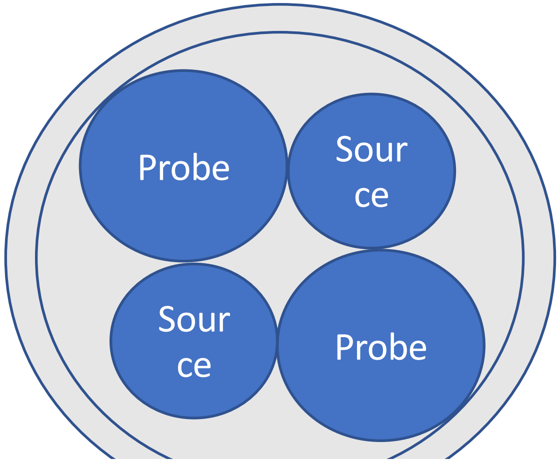


2- On-chip integrated mechanical filtering system

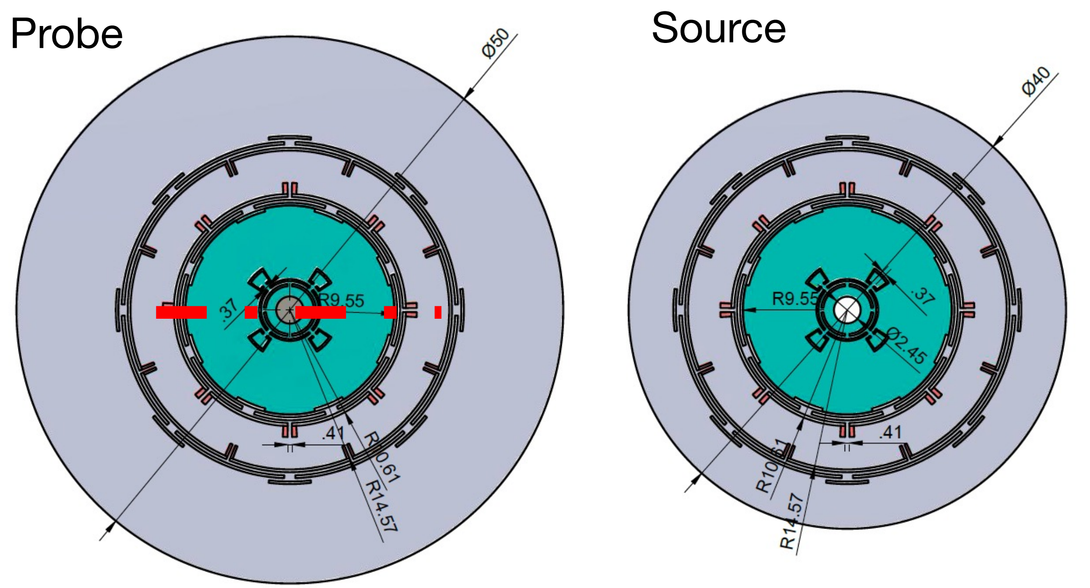
The support remains stationary during vibration.

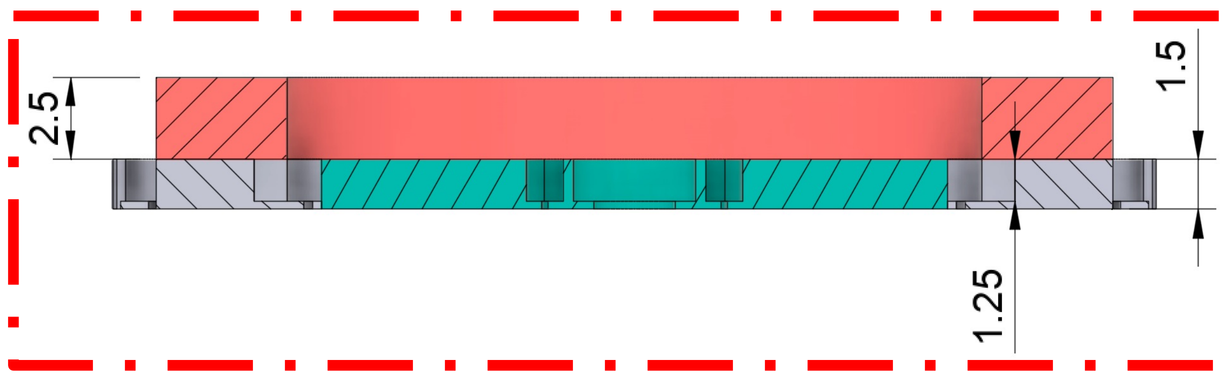
Resonating couple and requirements

TIFPA- Activity 2024-2025



6-inch wafer



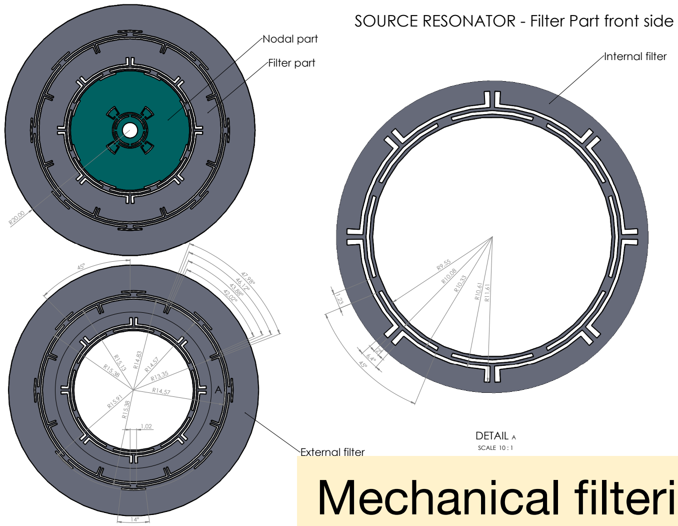


Requirements:
High Q-factors and frequency tuning of the resonating couple.

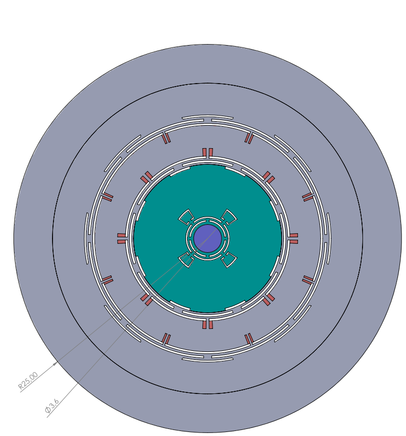
A frequency accuracy of 1% (of the main resonance) is expected from the microfabrication process, due to the high-aspect-ratio silicon structures. To fine-tune the frequencies of the two resonators, we must adjust them by evaporating gold (Au) onto the source of the resonators.

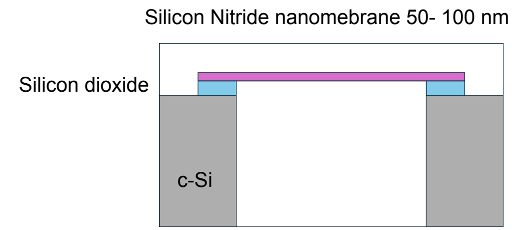
Further details of the resonator structure

TIFPA- Activity 2024-2025

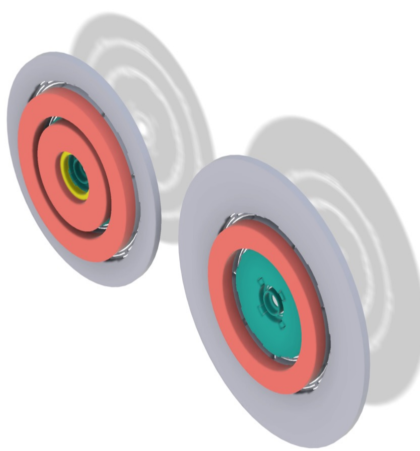


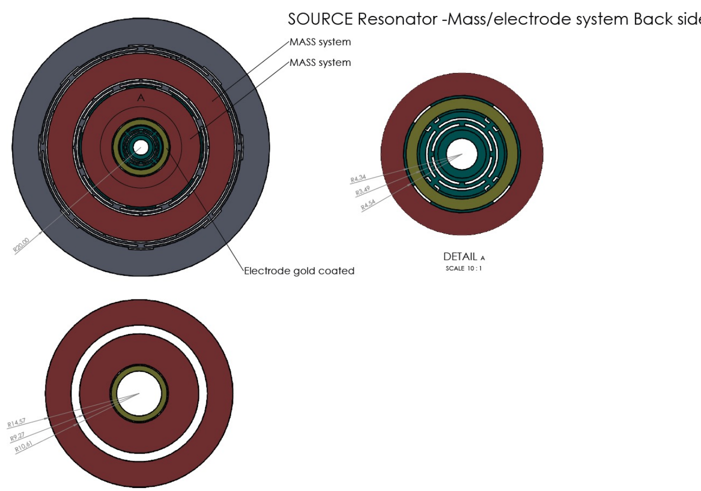
Mechanical filtering





Si_3N_4 membrane on the PROBE resonator





Masses and electrodes to tune the frequency of the main mode of the PROBE/SOURCE oscillator to 20 kHz.

Research Collaborative Agreement with SINTEF - Norway

Signed on December 2023

Collaboration Agreement
(n. TTB_23TIF_089)

Between

Istituto Nazionale di Fisica Nucleare (hereinafter "INFN"), an Italian Governmental Organization with its seat in via Enrico Fermi 54, 0044 Frascati (RM), Italy, represented by the Director of Trento Institute for Fundamental Physics and Applications (TIFPA), Francesco Pederiva

And

SINTEF AS, by its institute SINTEF Digital, department Smart Sensors and Microsystems, (hereinafter "SINTEF"), having a place of business at Gaustadalleen23 C, 0373 Oslo, Norway, represented by the Research Manager of Silicon Sensors Technology Group, Klaus Magnus Johansen.

hereinafter referred to as the "Party" and, if jointly, the "Parties."

WHEREAS

I. INFN is an Italian Public Research Organization which promotes, coordinates, and carries out scientific research in the field of nuclear, subnuclear, astroparticle physics and of the fundamental interactions, as well as research and technology development relevant to the activities in these areas by providing synergies with other research institutions and the business world.

Trento I.F.P.A.
C.F. 84001850589

Ordine di acquisto n. 1812 del 14-NOV-24
(Da citare in fattura, nelle comunicazioni e sugli imballaggi)
Vs. riferimento
Codice Fornitore INFN: 1332241
Ns. Riferimento **CIG B41BA75357**
Codice Univoco Ufficio di Fatturazione Elettronica: I4AX1G

Spett.le
SINTEF AS
Strindvegen 4
7034 Trondhiem Norvegia

Con la presente ci pregiamo ordinarvi quanto segue, alle condizioni sottoindicate:
Descrizione sintetica: **Servizio di microfabbricazione finalizzato alla realizzazione di prototipi di oscillatori in silicio allo stato dell'arte per studi di gravità quantistica**

QUANTITA'	DESCRIZIONE	SCONTO	%	PREZZO UNITARIO	IMPORTO
1,0	servizio di nano-microfabbricazione	0,00	0	120.000,00	120.000,00

TOTALE EUR : 120.000,00
TOTALE EUR **(Ivato):** 146.400,00
IVA AL 22% EUR 26.400,00

Clean–room costs sustained by SINTEF

120k euro + VAT – allocated with a procedure in November 2024 for three years – 8 tasks !!

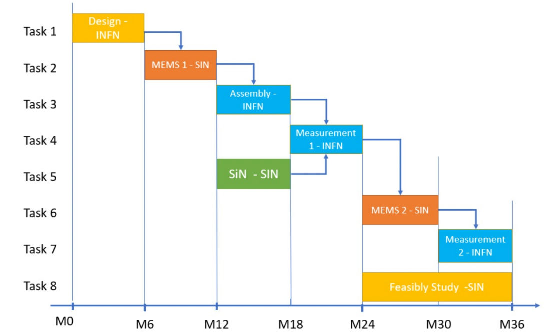


Figure 1: Gantt chart of the project

Kick-off 05-11-2024

Activities scheduling

TASK N°	DESCRIPTION	ESTIMATE COMPLETION BY	ASSIGNED TO
1	Finalization of the probe/source oscillator design, mask set design and fabrication process definition	Month 6	INFN
2	Microfabrication of the Probe/Source mechanical oscillator in monocrystalline silicon; microfabrication process of monocrystalline silicon masses for the frequency tuning system.	Month 12	SINTEF
3	Assembly of the probe and source oscillator with additional masses and measurement of frequency drift between two similar oscillators at room temperature;	Month 18	INFN
4	Measurement of mechanical quality factors of the probe at cryogenic temperatures, and optical and mechanical characterization of silicon nitride nanomembranes at room temperature	Month 24	INFN
5	Microfabrication and stress calibration of silicon nitride nanomembranes on test wafers	Month 18	SINTEF
6	Microfabrication of the probe oscillator with the integration of the silicon nitride membrane on a blank silicon wafer	Month 30	SINTEF
7	Characterization of the Source/Probe pair tuning within 1Hz with gold film deposition	Month 36	INFN
8	Feasibility study for the excitation electrode of the source resonator. Planning of possible implementations into the Source resonator design	Month 36	SINTEF

In the framework WP1 merging of T1.2 and T1.5 of the CdR

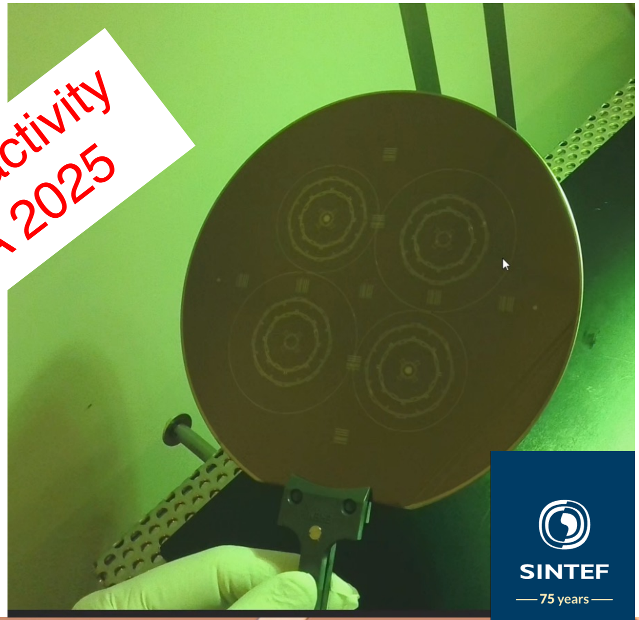
People involved:

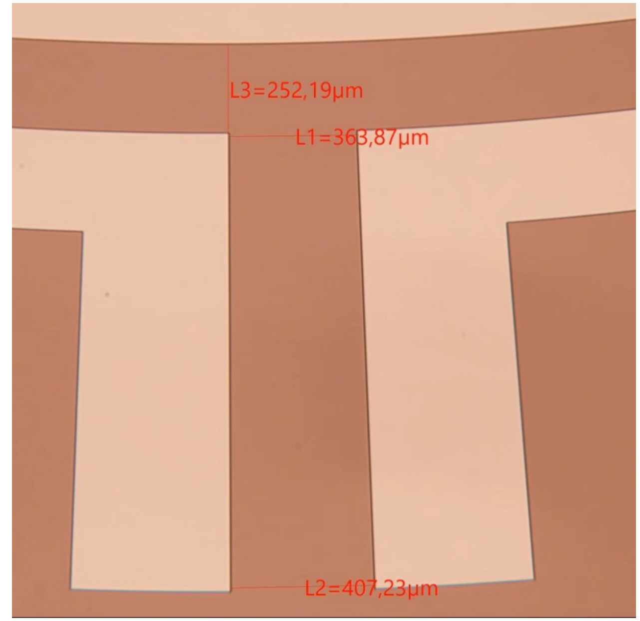
INFN
Dr. Enrico Serra
Dr. Michele Bonaldi
Dr. Antonio Borrielli

SINTEF
Dr. Guido Sordo
Dr. Anand Summanwar
Dr. Daniel Nilsen Wright
Dr. Klaus Magnus Johansen

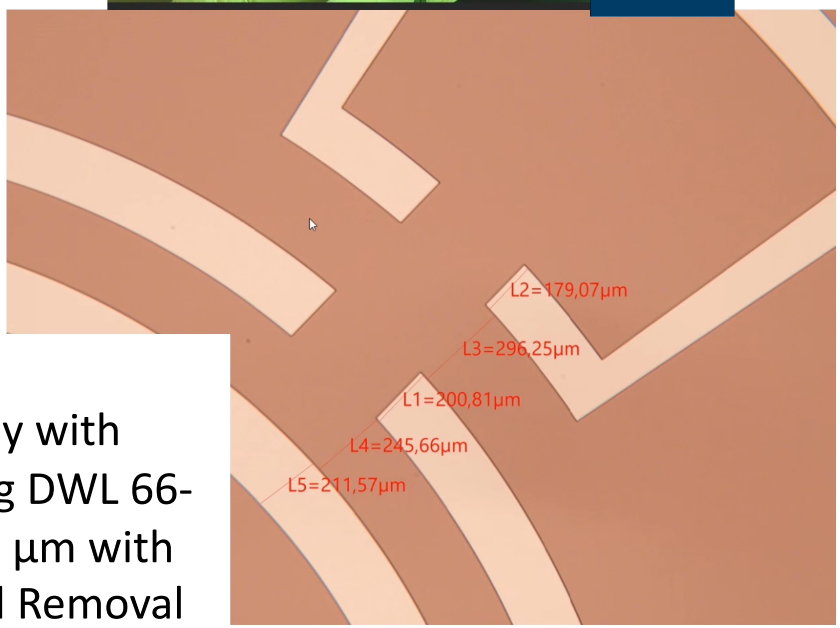
➢ Microfabbrication at SINTEF WP1 - T1.2/T1.5 del CDR

Collaborative activity
Sintef- TIFPA 2025

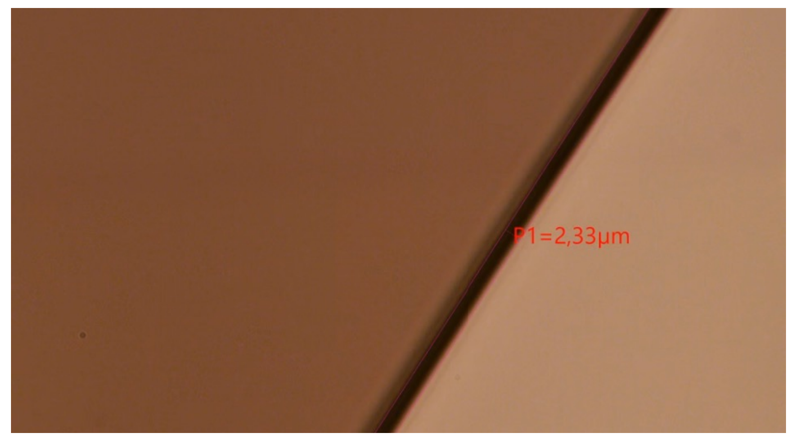




Check geometry



Maskless lithography with Heidelberg DWL 66- profile 2.3 µm with Edge Bead Removal

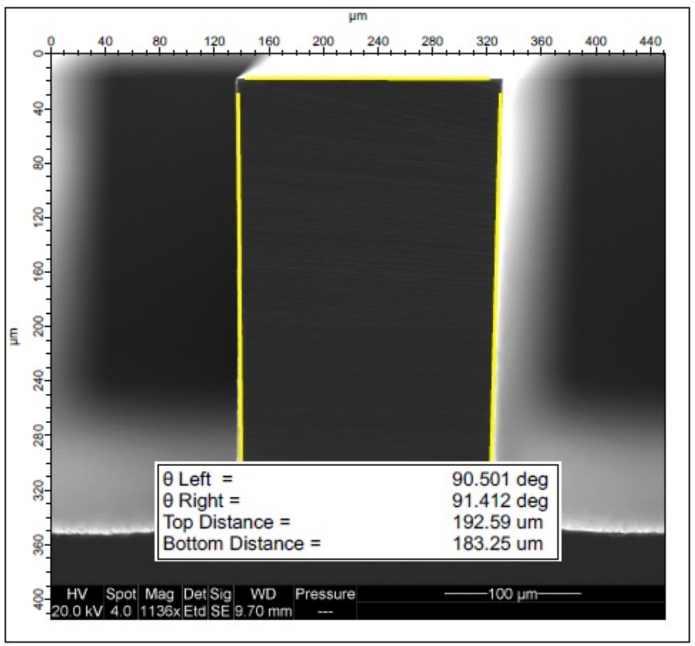


Defining the resist profile

FETCH mask lithography and Deep-RIE on SPTS machine with Bosch process.

Collaborative activity Sintef- TIFPA 2025

Two test wafers have been etched with different DRIE recipes. The wafers have been diced and measured in the SEM at 5 positions (from 0 to 4)

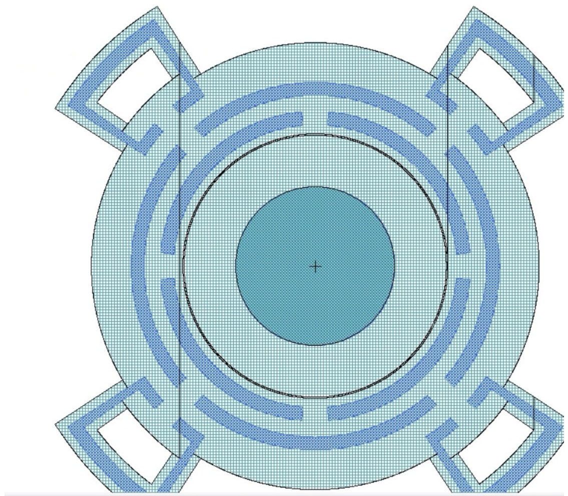


Selected the best deep-RIE Bosch recipe for the profile at the front side

SINTEF 75 years

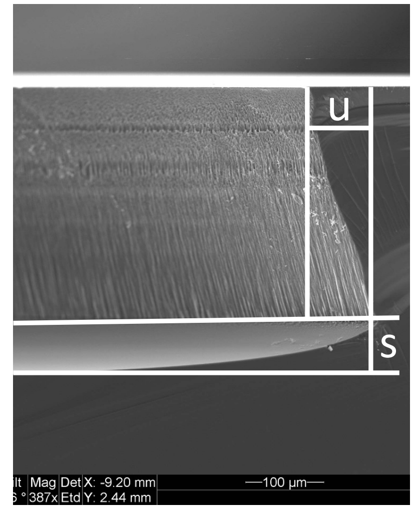
Developing microfabbrication strategies with SINTEF

Backside etching

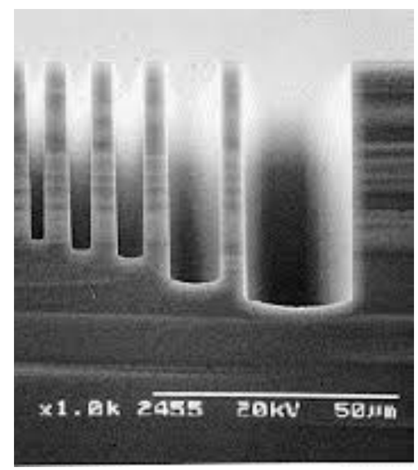


Collaborative activity
Sintef- TIFPA 2025

Bottom surface (undecut **u** and curvature **s**)



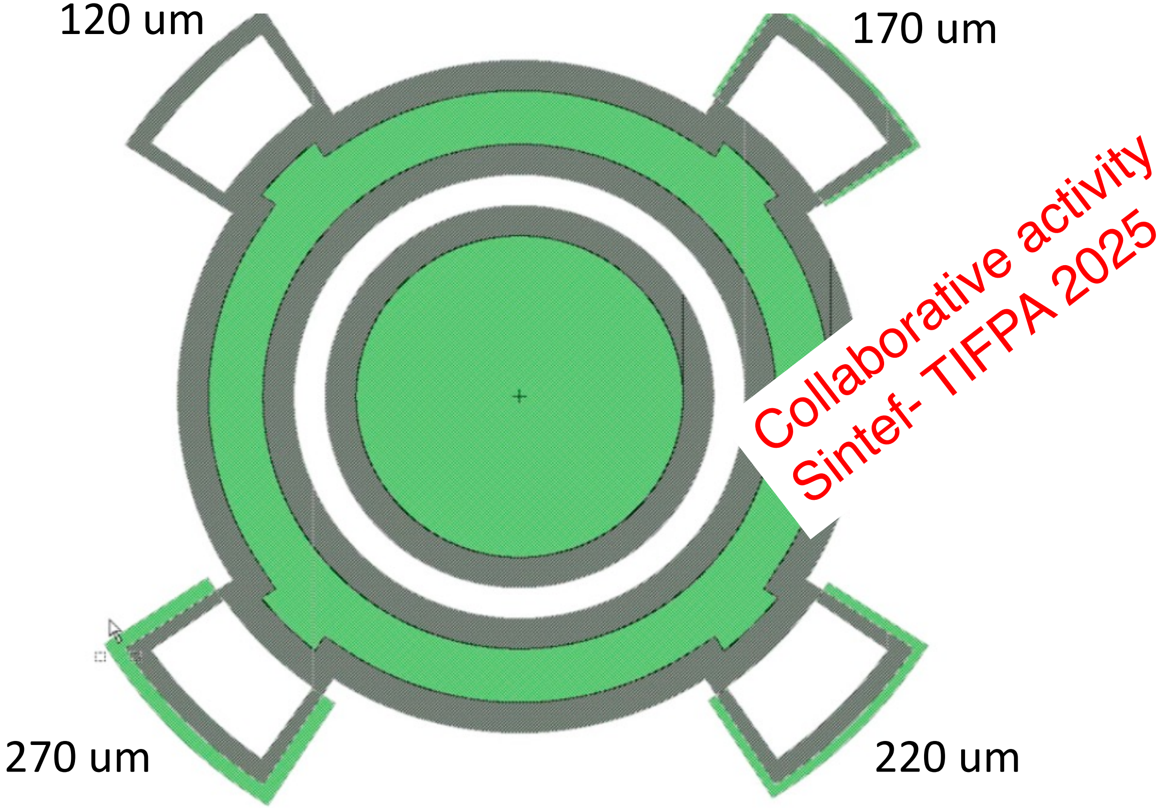
Aspect Ratio Dependent Etching

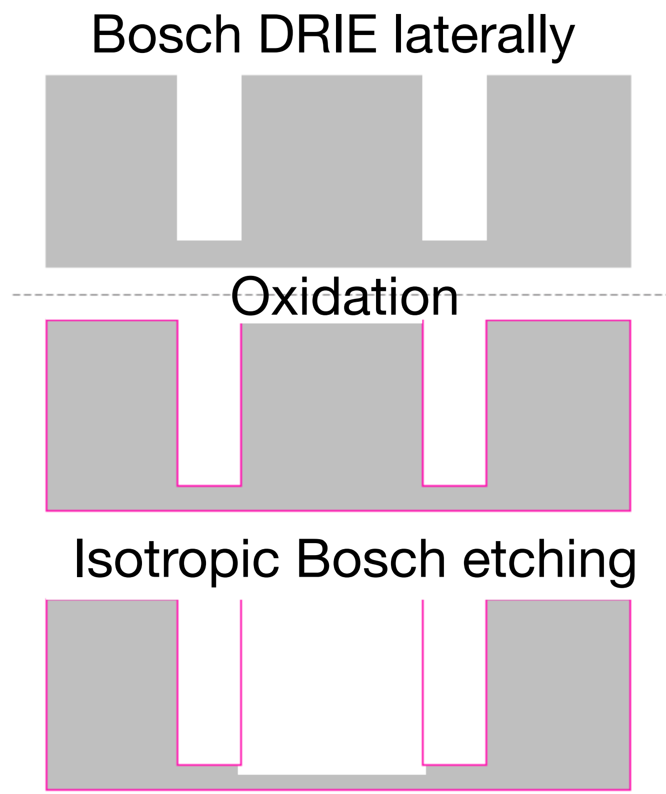


The internal ring can be etched away due to area loading during the Deep-RIE step – ARDE effect

We need a new etching procedure to keep profiles straight.

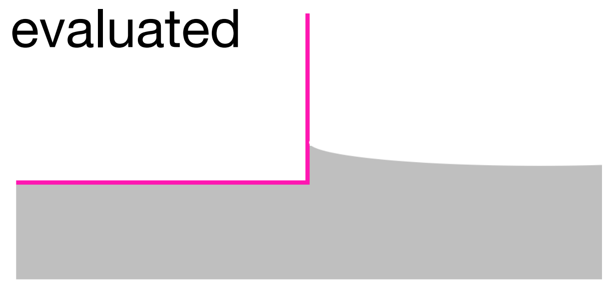
Ongoing technological solutions Sintef





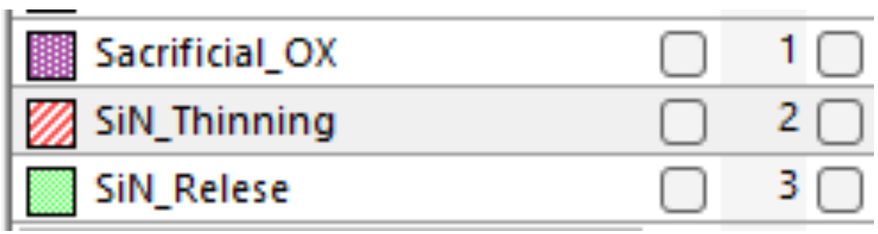
We are implementing a strategy for making the area uniform loading with Deep-RIE

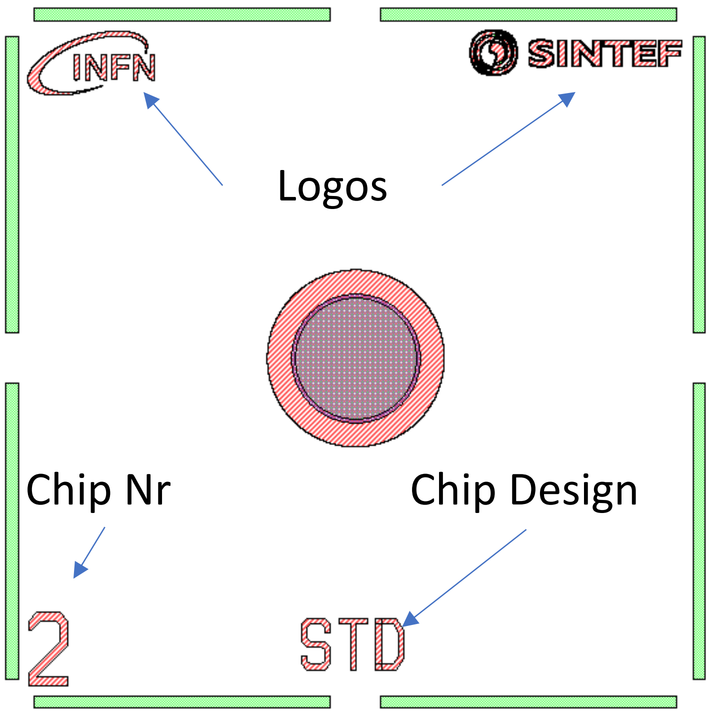
Little changes in the spring constant to be evaluated

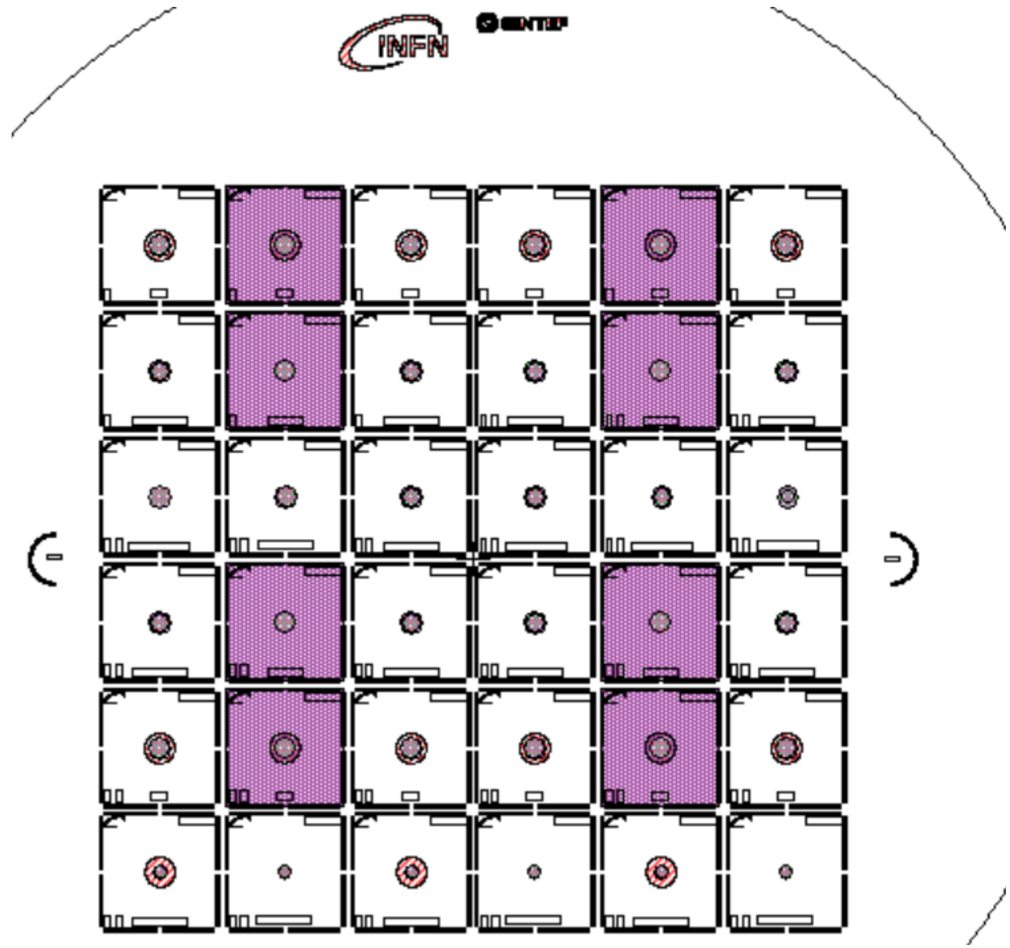


Integration of the membrane in the Probe

Circular stoichiometric Si_3N_4 membrane for testing the optical quality of the film, the stress and possible estimation of the Q-factor for a 100 nm thick membrane.





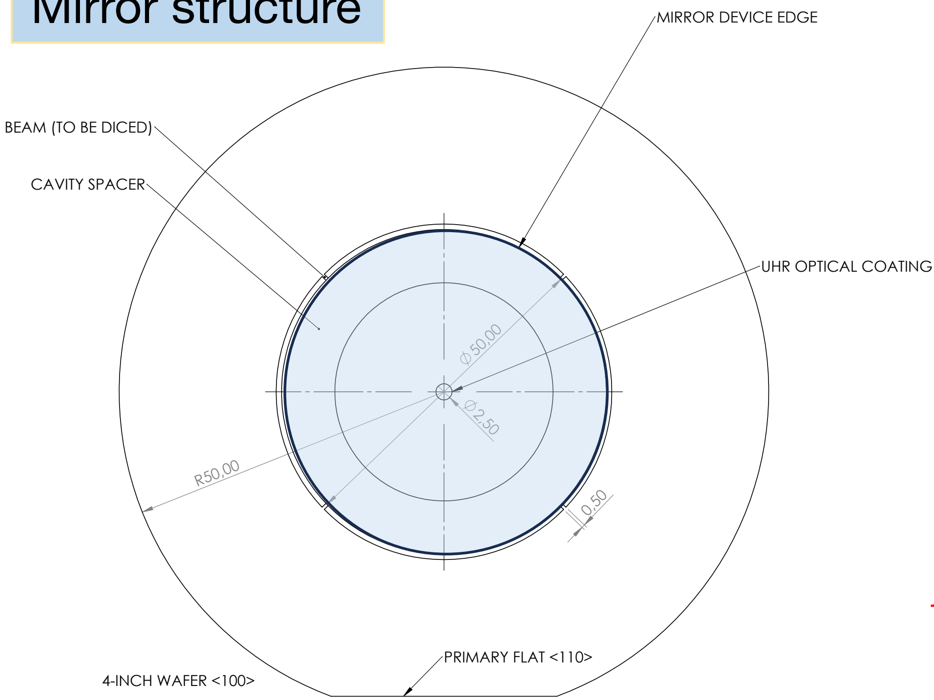


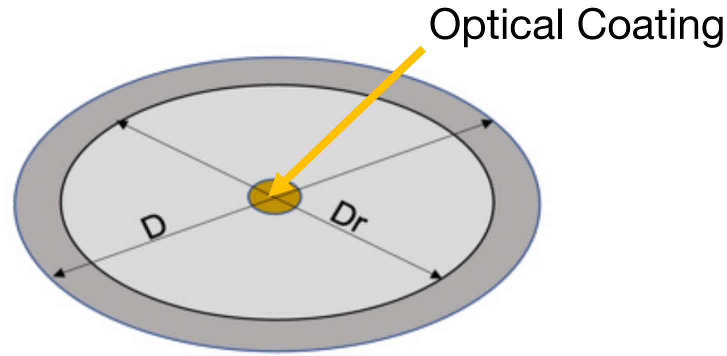
Collaborative activity by TIFPA 2025

The UHR mirror/ EM shield on a 4-inch wafer

WP1 - T1.6 del CDR

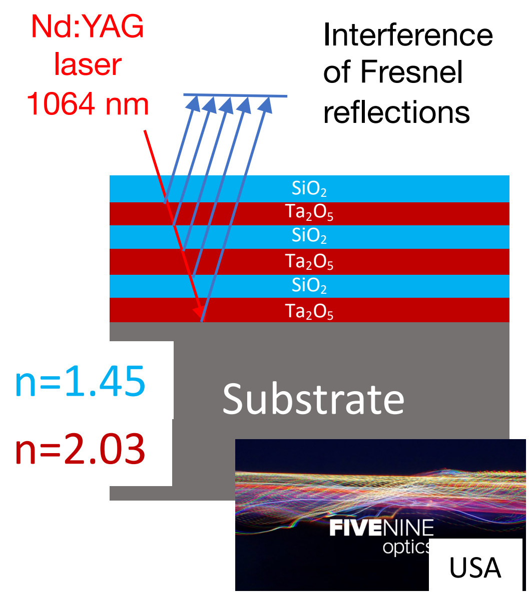
Mirror structure

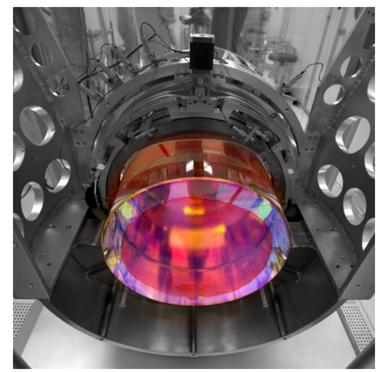




38 layers $\lambda/_4$ Ta_2O_5 /SiO_2
Ion–Beam Sputtering with R > 99.999% @ 1064nm @ 0° (T 3-5 ppm) – Our coating is a modified version with 39 layers and last layer SiO_2 $\lambda/_2$

Silicon-on-insulator wafers 22.5/1/300 um – two diameters, Dr=34 and 40 mm



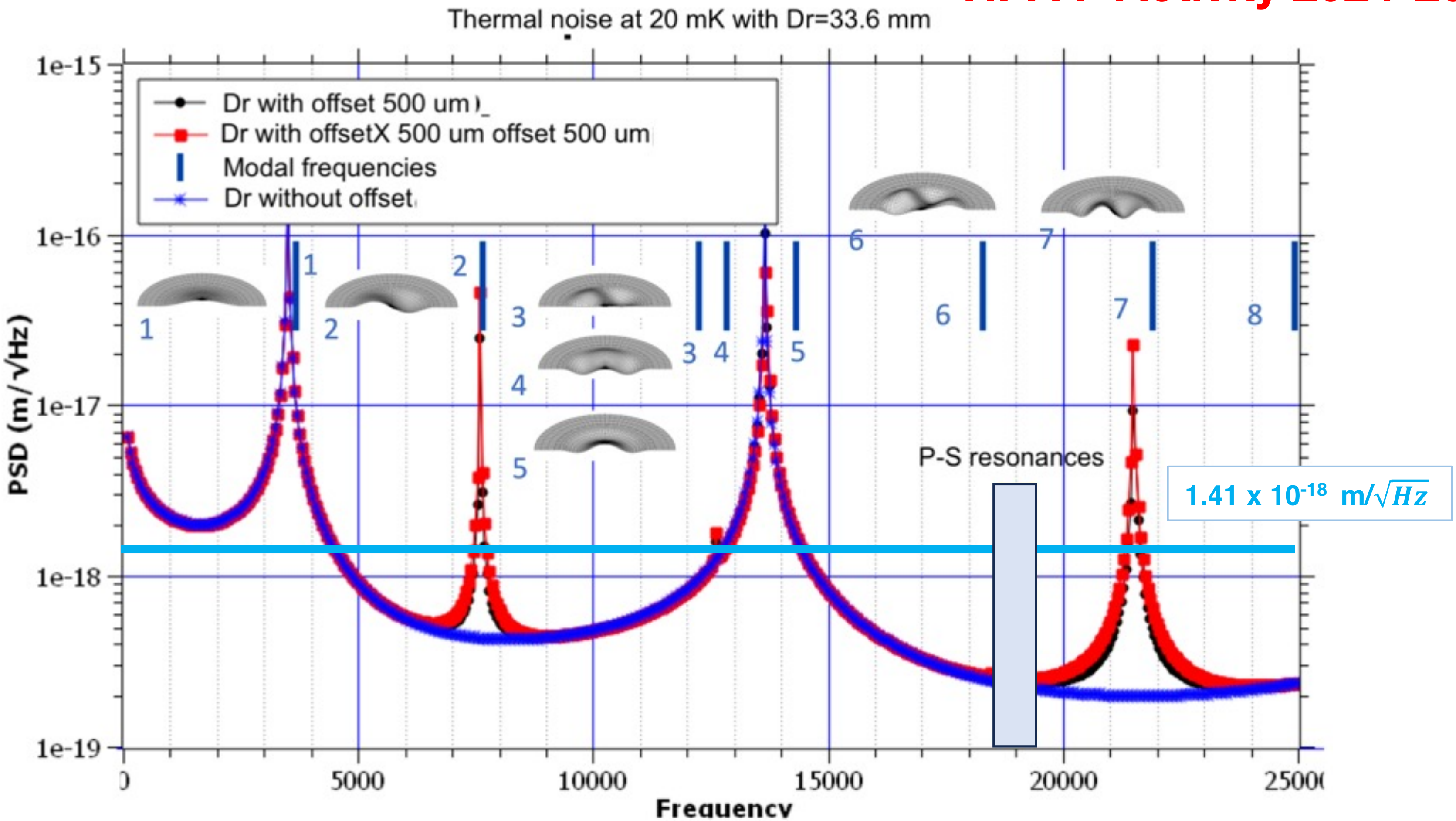


UHR coatings on fused silica in Advanced Virgo GW detector

Delft University of Technology
THz sensing group dr. Paolo Sberna

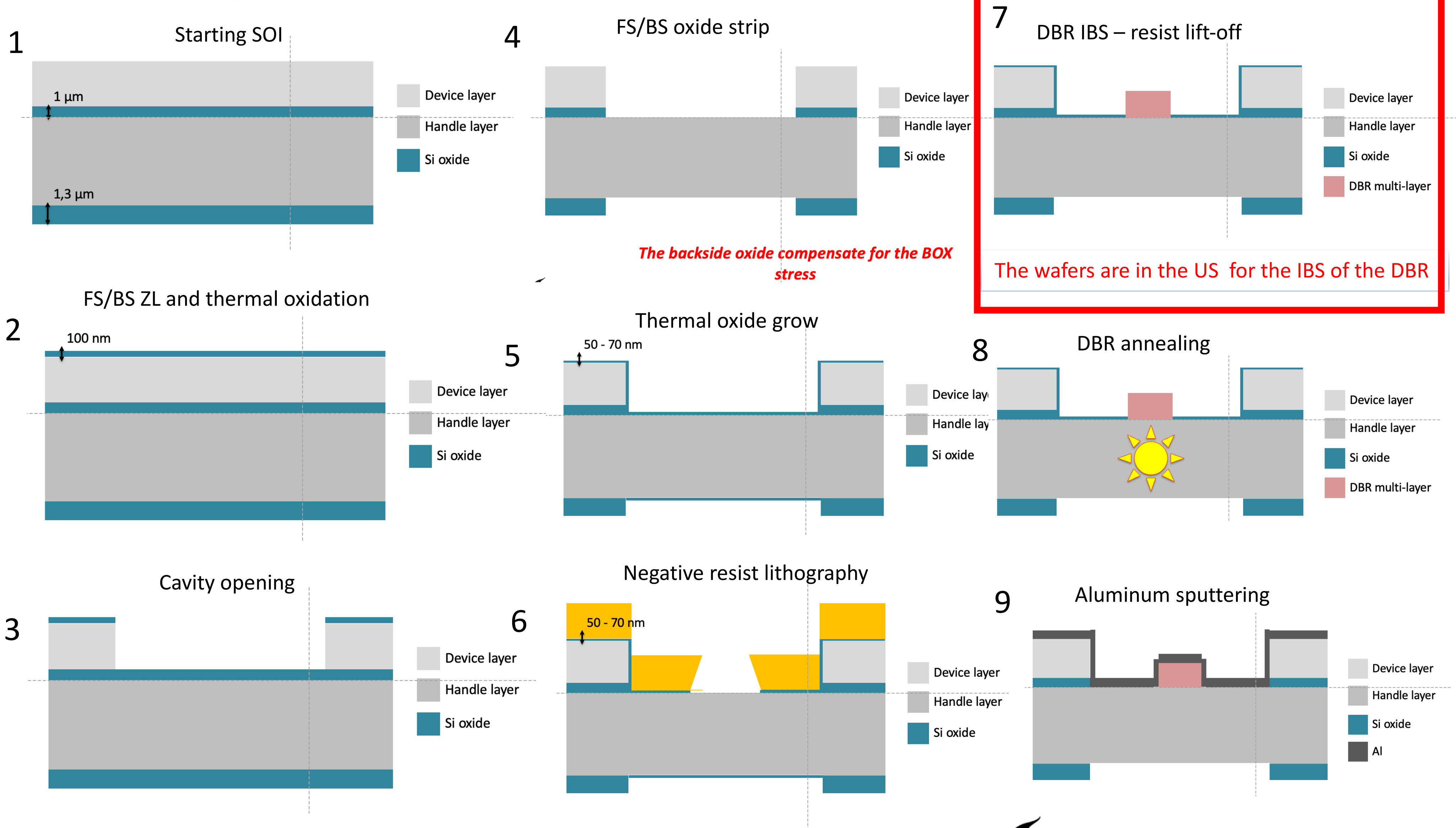
Design of the UHR mirror/ EM shield

TIFPA- Activity 2024-2025



In the case of **feedback cooling,** the upper limit for displacement thermal noise of the optical cavity mounted on a cryostat is **1.41×10^{-18} $m/\sqrt{Hz}$**

Process flow of the micro-fabricated mirror 1

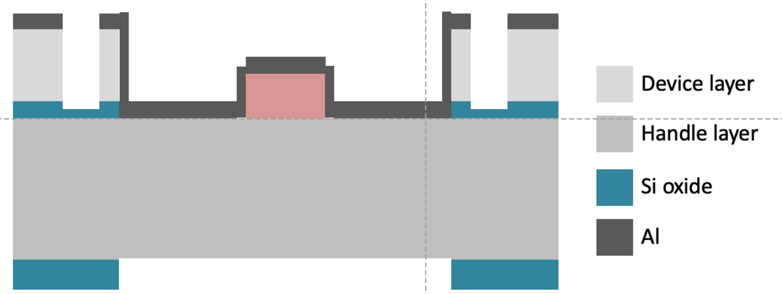


Collaborative activity TUD- TIFPA 2025–2026

Process flow of the micro-fabricated mirror 2

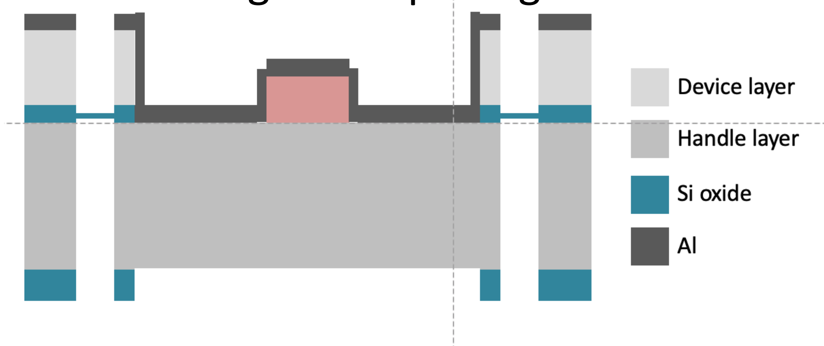
FS dicing lines opening

10



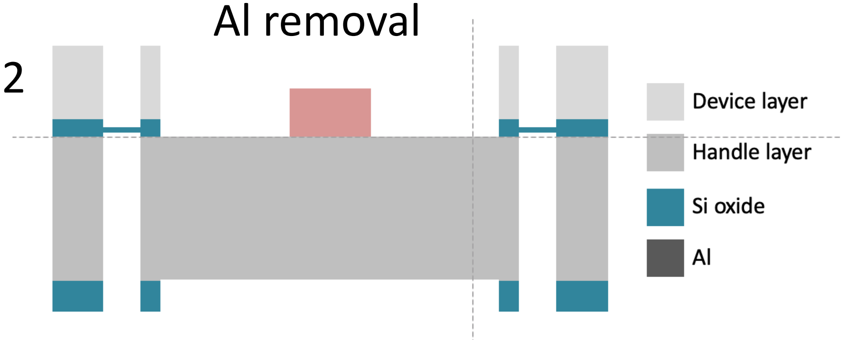
BS dicing lines opening

11



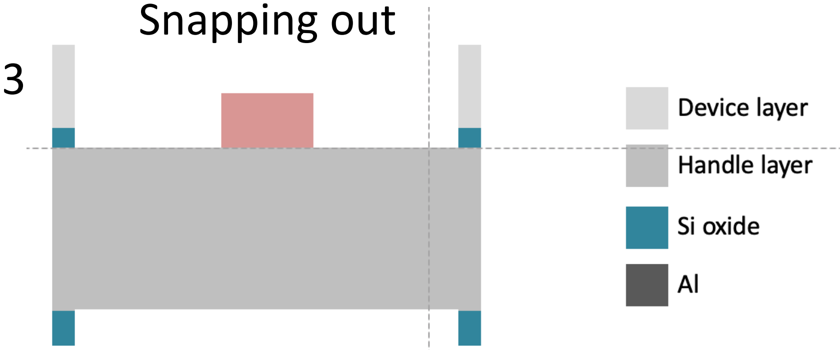
Al removal

12



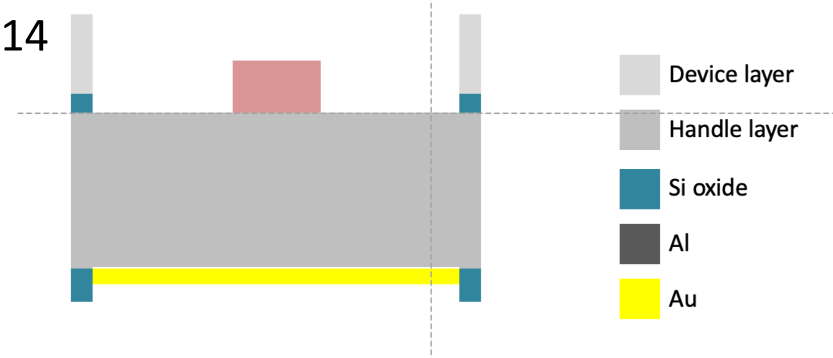
Snapping out

13



BS Au coating

14

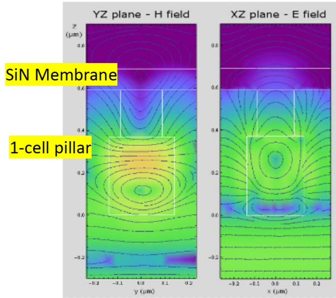


Collaborative activity TUD- TIFPA 2025–2026

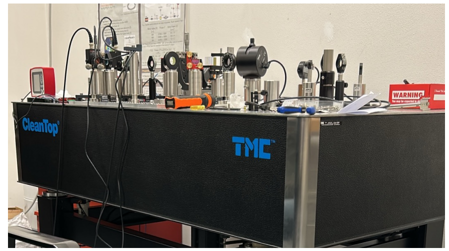
Towards HR reflecting coating made by PhCs

A photonic crystal coating that can be integrated in a Si_3N_4 membrane.

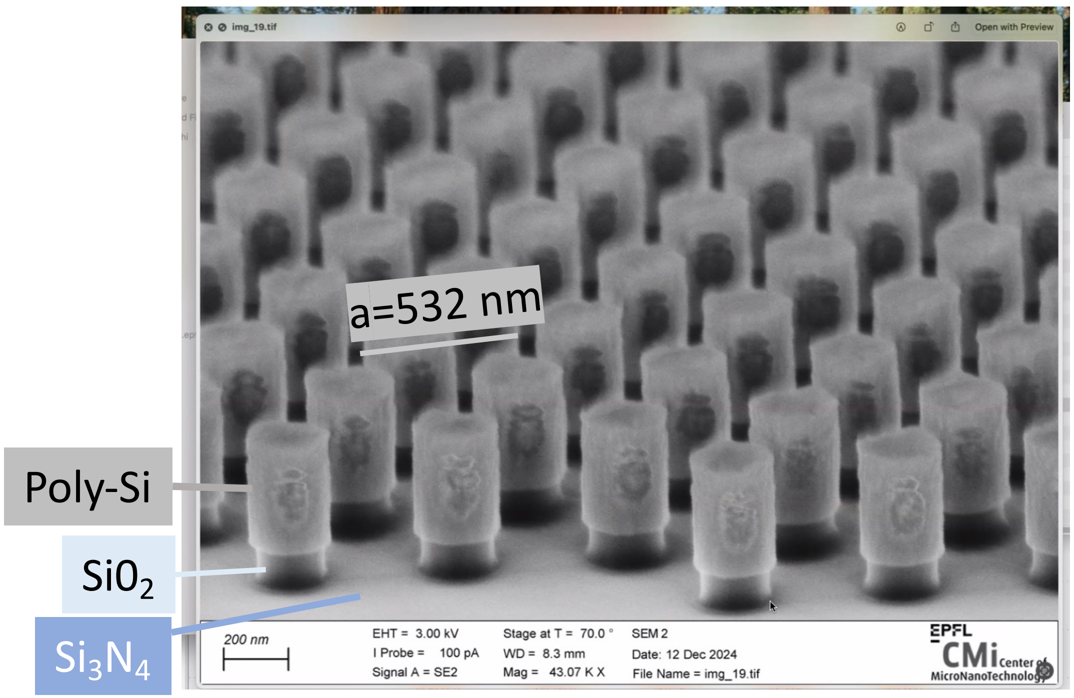
Design & measurements INFN-TIFPA -2025

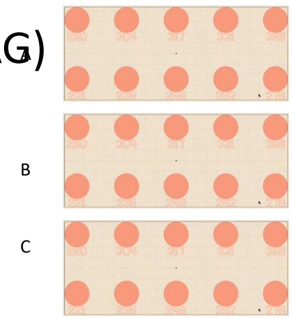


Measurement set-up

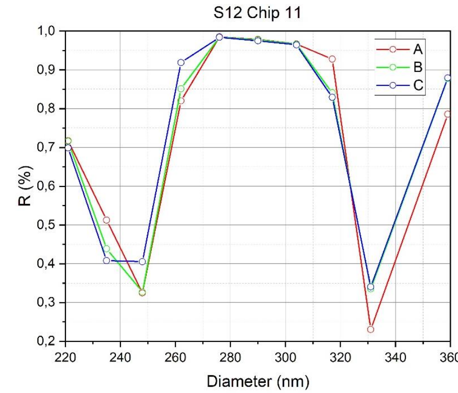


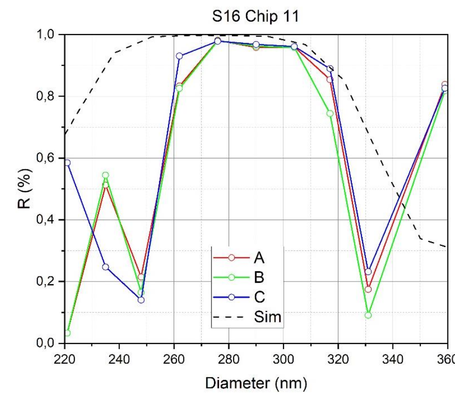
Hexagonal reticle with periodicity $a = \lambda/2$ (laser Nd: YAG)

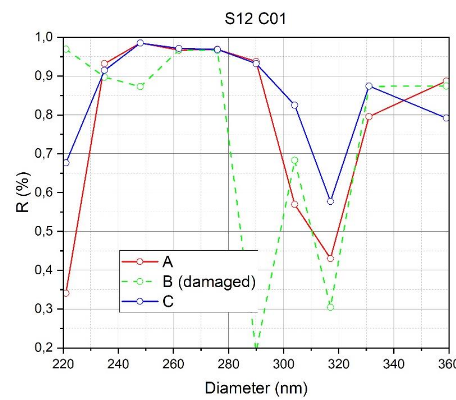




Max reflectivity 98.5% at 1064 nm







Courteously EPFL from Laboratory of Photonic Integrated Circuits and quantum measurements - Kippeberg, Zichoshi

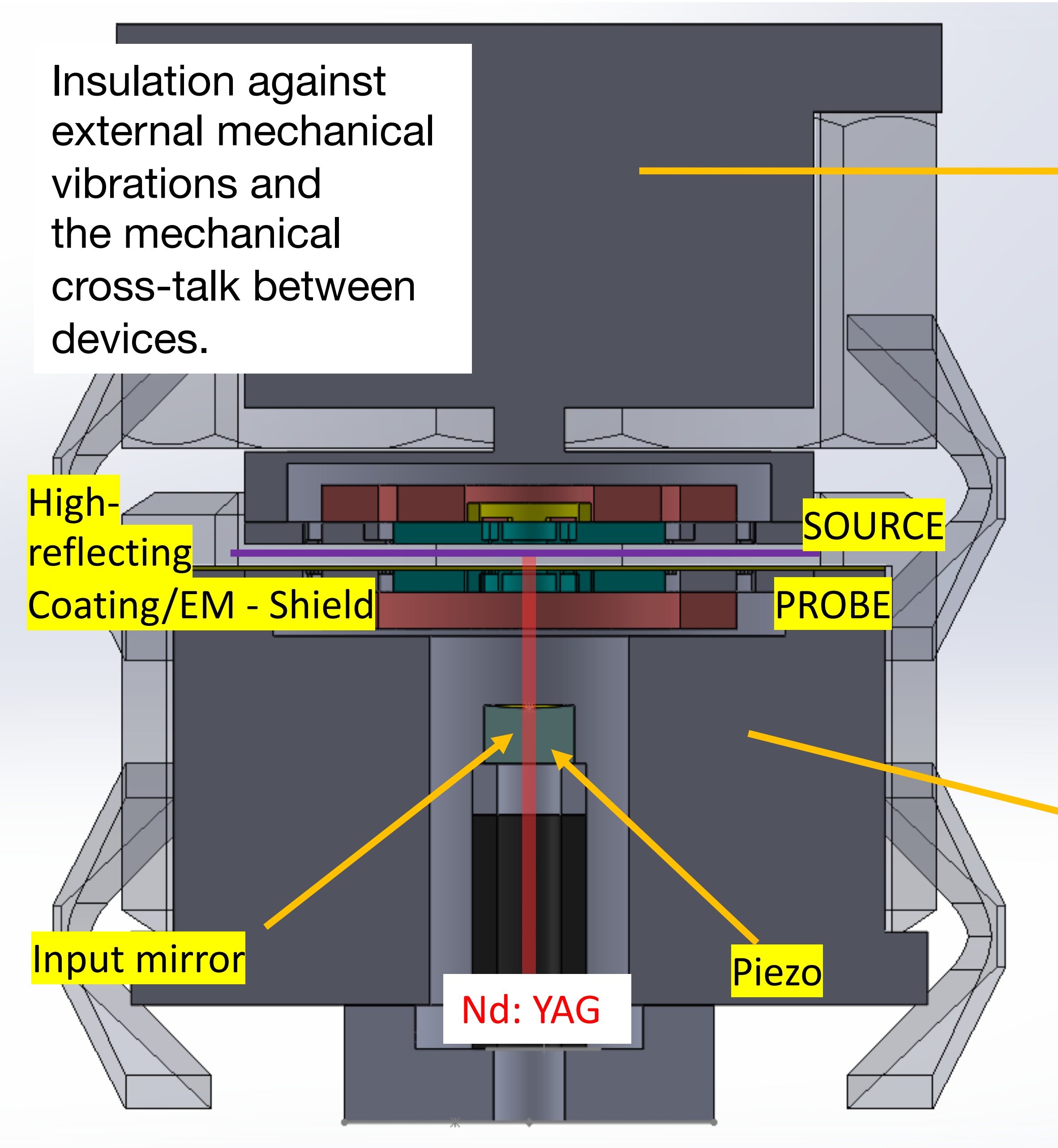
INFN

Istituto Nazionale di Fisica Nucleare
TIFPA
Trento Institute for Fundamental Physics and Applications

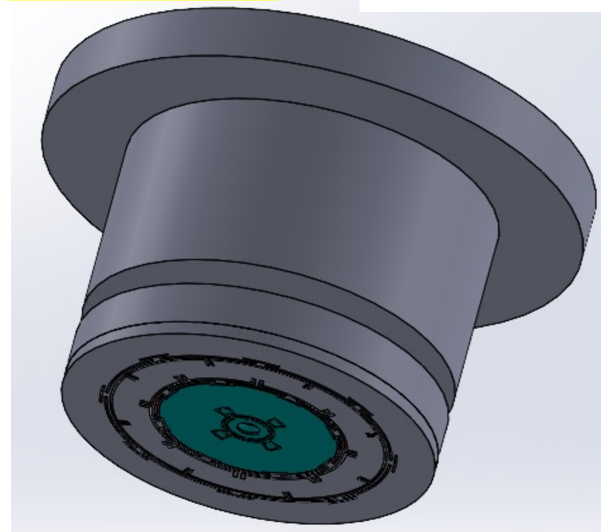
Design of the optical cavity

TIFPA activity 2024

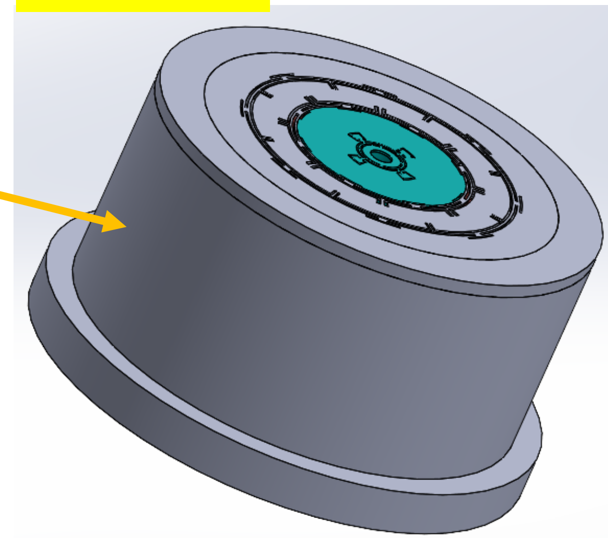
Insulation against external mechanical vibrations and the mechanical cross-talk between devices.



Source holder



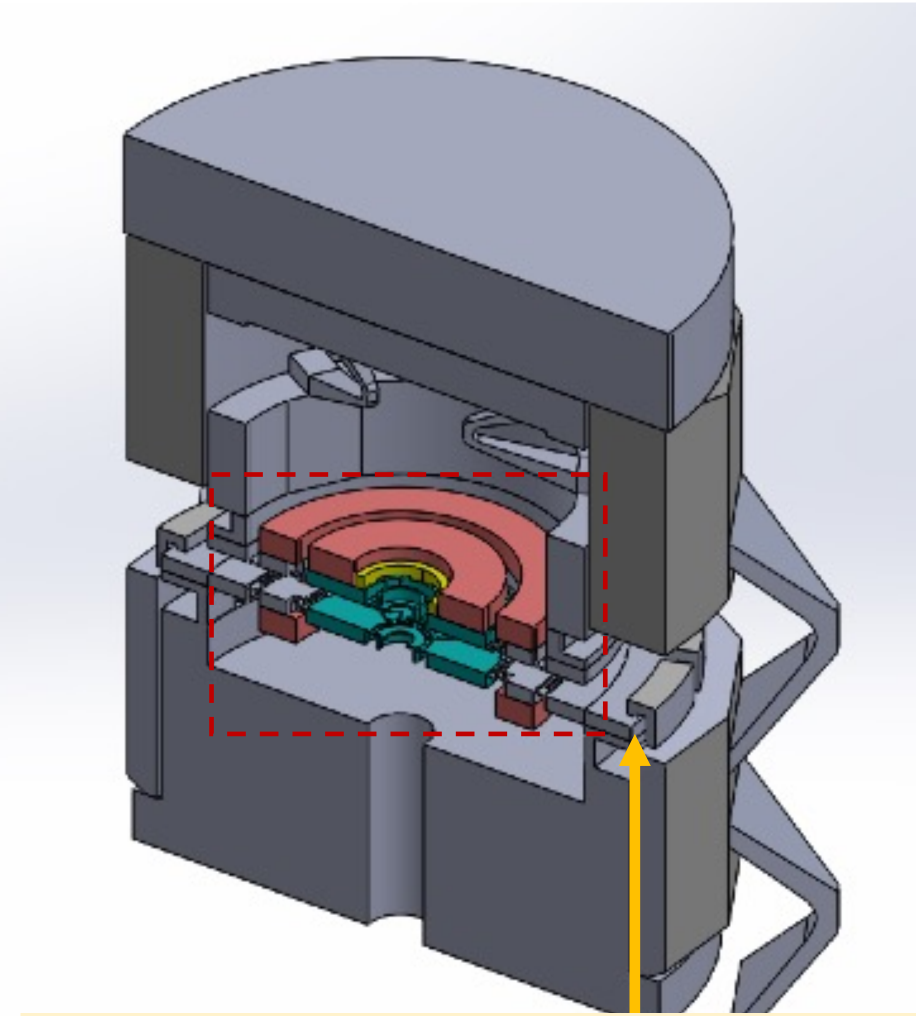
Probe holder

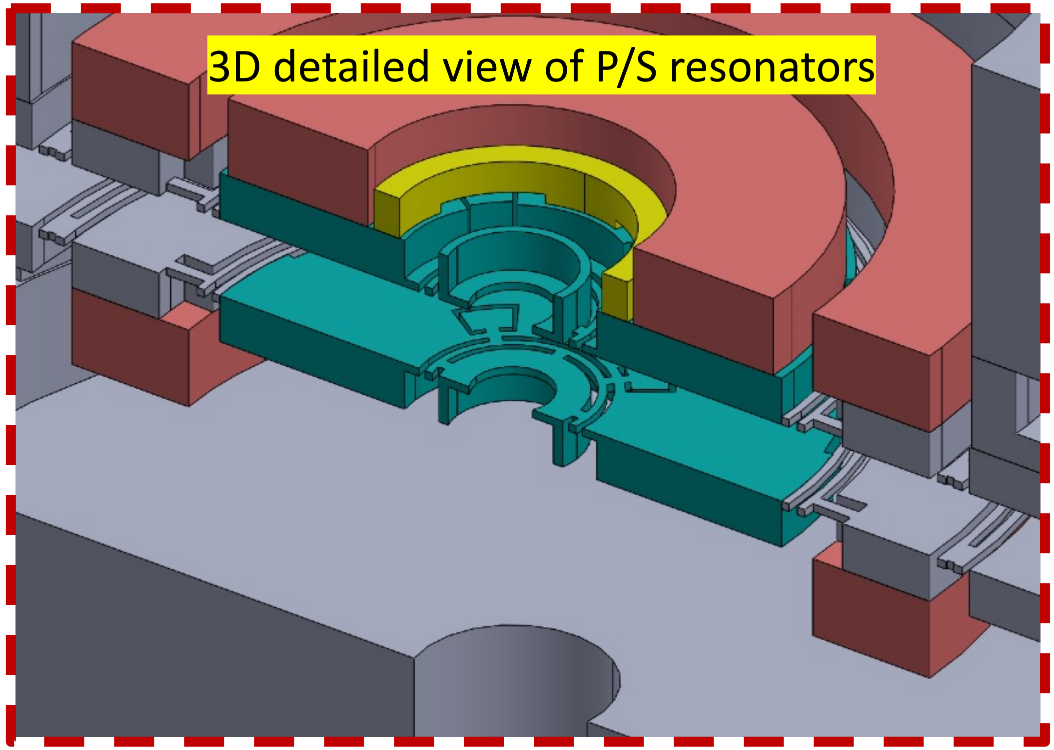


Reducing thermal stress due to the cryogenics

Tifpa Activity 2025 -2026

We are currently working on accurately measuring the contact resistances of the materials in the stack by clamping the oscillators. This step is essential to ensure that the subsequent simulations are reliable and meaningful.

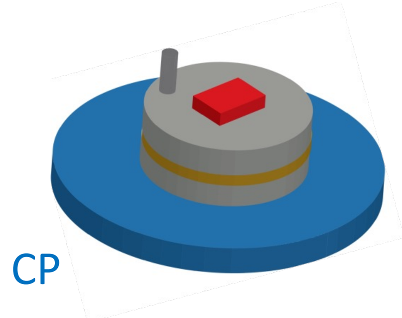




Spring system to reduce stress in the PROBE resonator due to cooling. Dimensions of the probe external ring are not fixed in the design; possible variations on the **PROBE flexural joint dimensions are still considered.**

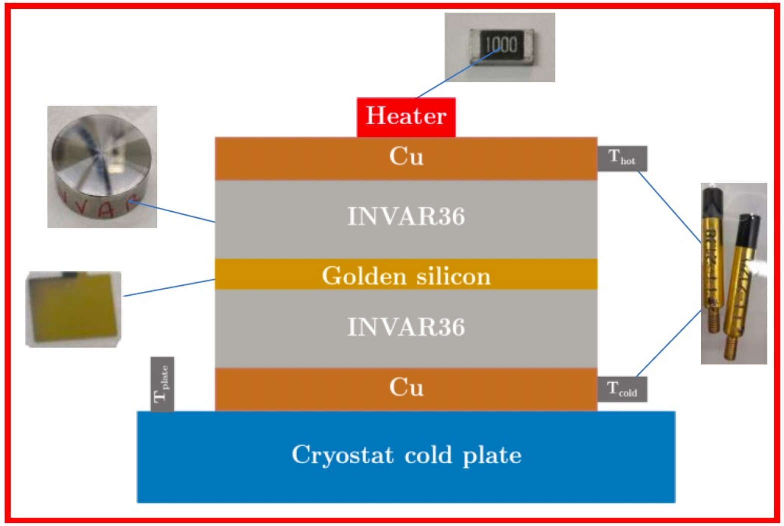
Thermal Conductivity Measurement

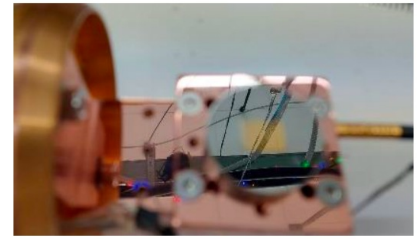
Determining the temperature gradient between the cold plate and the resonating part

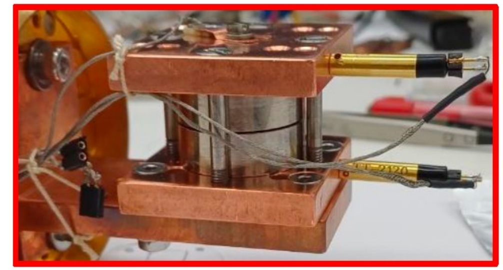


The gradient is determined by the Kapitza thermal contact resistance.

Further reduction is expected with gold plating of INVAR and Cu. Measurement are underway.

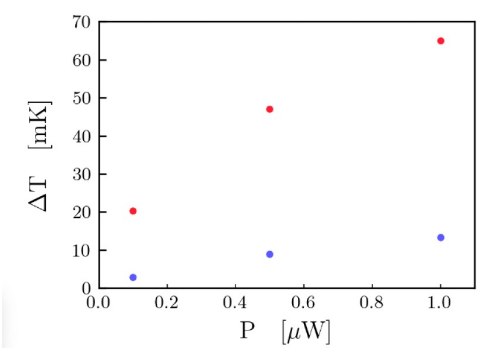




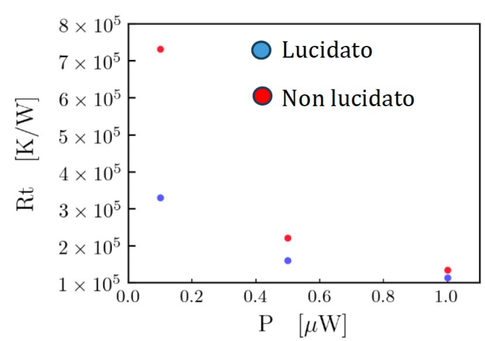


eratura efficace del

Gradiente Rame - Rame



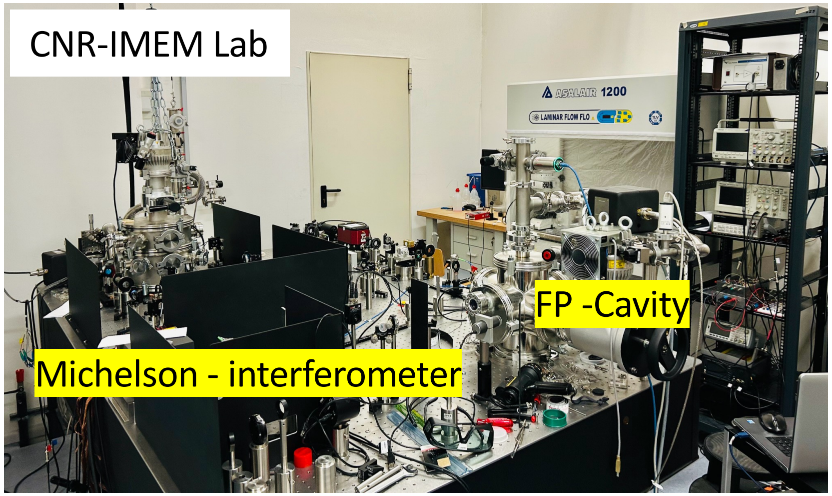
Resistenza termica



INFN-PG
WP4-CDR

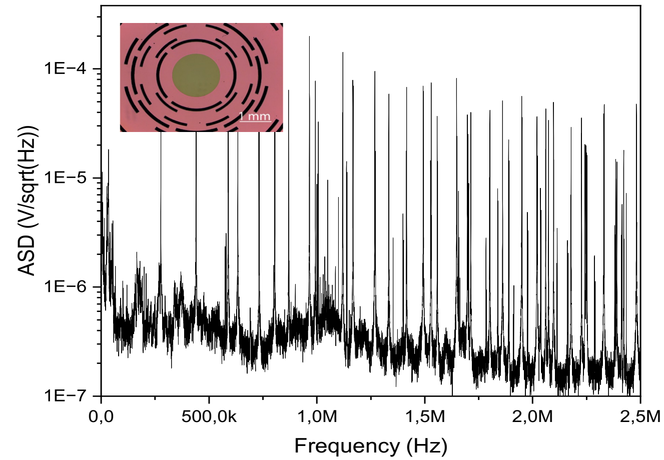
Essential for accurate thermal stress simulations to prevent potential silicon fracture. The thermal–stress simulation of the optical cavity will be done by TIFPA.

Sinergy with FBK – (2024 -2025)



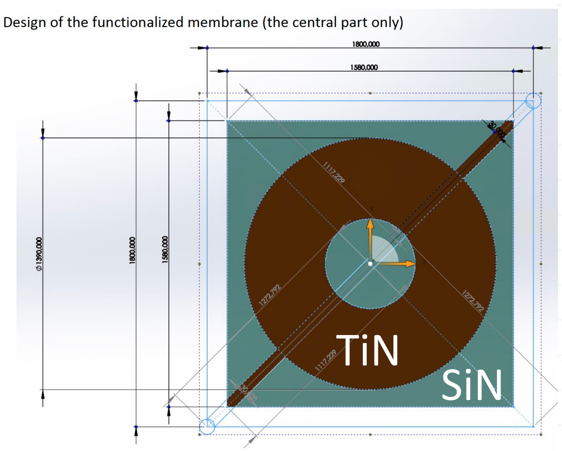
A luglio verrà emessa nota di debito per L'attività finora svolta con Accordo MINaTAP

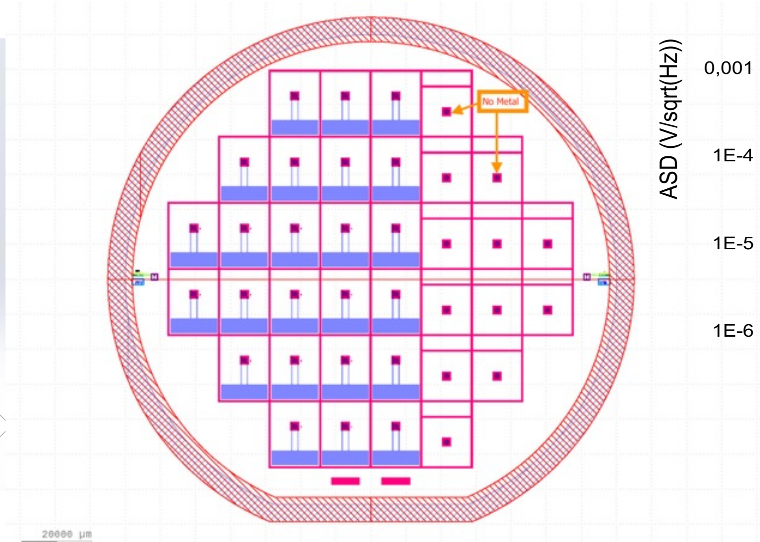
(Top) Cavity measurement with PHD scheme and MIM
(Bottom) Interferometric measurement on FBK SiN membranes.

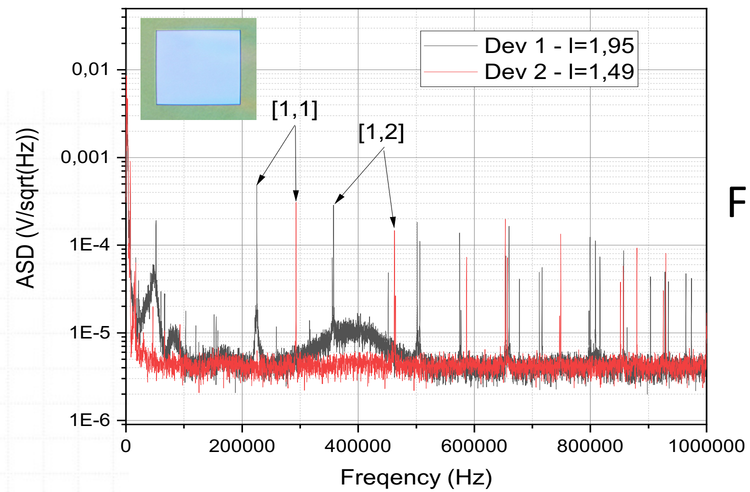


TUD

The work is about to be completed within the next two months.
Collaboration with TUD for developing a low-stress superconducting TiN film is underway.



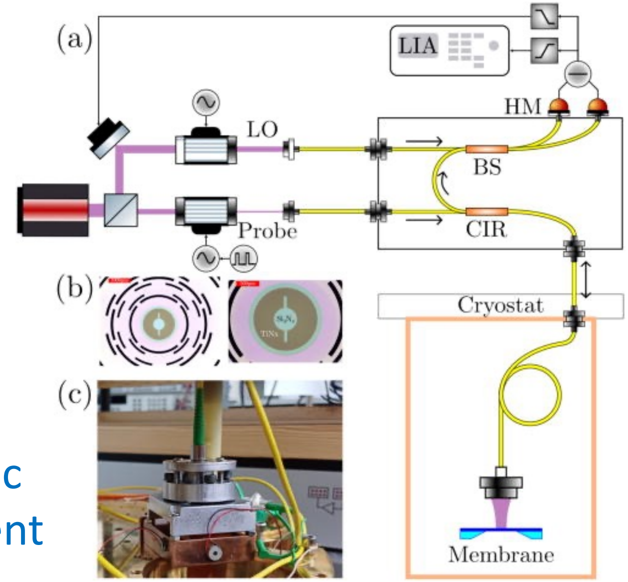




FBK

FBK Picciotto, Nawaz

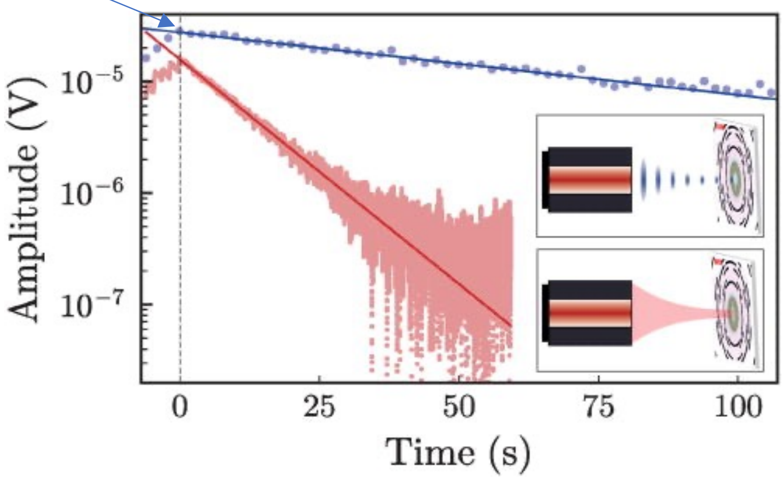
Q-factor measurement at ultra-cryojenic temperatures (2025)



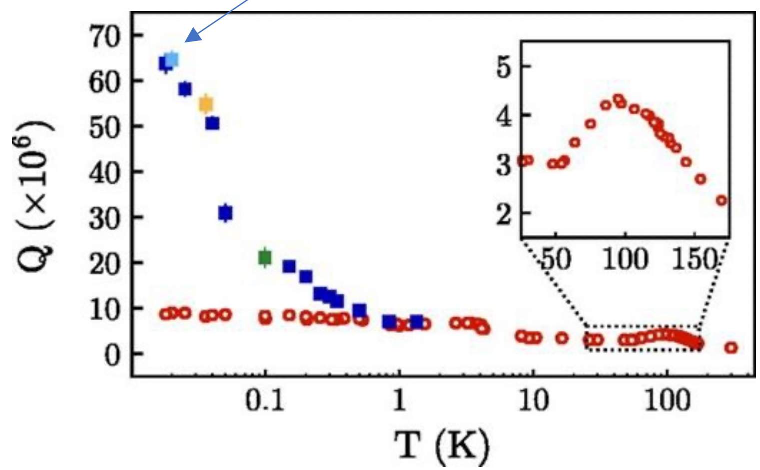
As in the GRAFIQO device (featuring an on-chip insulation stage), the Q-factor of a SiN membrane was measured at temperatures below 1 K.

The Q-factor is extremely influenced by the optical power of c.w. for temperatures < 1 K

Stroboscopic measurement



Peak value 64 x 10^6



Appl. Phys. Lett. 126, 174002 (2025)

Sinergia con PRIN2022

Trasduzione Quantistica e Rilevazione con Sistemi Opto-Elettro-Meccanici

GRAFIQO Workpackages	TIFPA activities in 2026
WP1: Design and fabrication of P-S devices **WP3:** Study and reduction of electrostatic coupling **WP5:** Analysis and possible reduction of acoustic noise at 20 kHz **WP6:** Design and implementation of the opto-mechanical system	**Microfabrication process for P-S pair:** Final realisation of the prototypes, optimised in the P-S geometry. **Development of the optomechanical characterisation setup** and fabrication of support structures for the P-S pair. **HR mirror/shield microfabrication:** process validation and completion of the final devices **Oscillator support design in the optical cavity:** Reengineering of supports to prevent fractures caused by differential contraction at cryogenic temperatures. Awaiting characterisation of thermal contact resistance.

Impegni di spesa/missioni GRAFIQO	al 30/06/2024	al 31/12/2024
Lavorazioni meccaniche per la realizzazione di supporti in rame per la caratterizzazione Q meccanico a temperatura ambiente dei prototipi di oscillatori Probe-Source.	0€	4000 €
subtrati costituiti da wafer di silicio monocristallino DSP orientazione <100> o wafer SOI silicon-on-insulator.	0€	3000 €
Missioni coordinamento Italia / missione estero TUD / Sintef	3.722,91 €	4.277,09
	3.722,91 €	11277,09

FTE & richieste finanziarie TIFPA 2026

Dettaglio FTE - TIFPA	**2026**
Dr. Michele Bonaldi (Associato Dip. FBK-CNR)	0.7
Dr. Antonio Borrielli (Associato Dip. CNR-IMEM)	0.7
Dr. Serra Enrico (Dip. Tecnologo TIFPA)	0.7
TOT	2.1

Richieste finaziarie TIFPA	**2026**
Contributo centro TIFPA acquisto licenza annuale Autodesk – Fusion per progettazione maschere litografiche. Si inserisce 1k euro in quanto il db chiede multipli di 0,5k euro. La spesa effettiva sarà di 0,8k euro	1k
Missioni Italia di coordinamento (3 persone) almeno 2 missione. Missione attività di laboratorio estero (1 persona) con partner di ricerca TUD e SINTEF Previste almeno 2 missioni	10k
Componenti elettronici per feedback di stabilizzazione della temperatura per camera da vuoto dell'interferometro Michelson. Necessario per la verifica delle frequenze di risonanza di source e probe (tuning).	3k
Subtrati costituiti da wafer di silicio monocristallino DSP orientazione <100> o wafer SOI Silicon-On-Insulator.	4k
TOT	18k

- Rimandiamo acquisto Au Coater – Stiamo testando presso la TU Delft l'evaporazione di Au su silicio.
- Acquisto di 146k euro presso Sintef servizio microfabbricazione nel 2024. Il budget copre attività di microfabbricazione nel periodo 2024-2027. Potrebbe nascere la necessità di incremetare la spesa del servizio nel 2027 a causa aumento costi processi che impiegano tecnologie (deep-RIE) basate su gas SF_6.

Publications 2024-2025

Project GRAFIQO (CSN2) - Year 2024 - (Validated on 2025-04-09T13:30:33.975)

To modify these information please refer to [The INFN Products Database]()

Title ↑↓	Authors	Journal
Coulomb coupling between two nanospheres trapped in a bichromatic optical tweezer	Deplano, Q. et al.	OPTICA
Generation of stable Gaussian cluster states in optomechanical systems with multifrequency drives	Yazdi, Nahid et al.	QUANTUM SCIENCE AND TECHNOLOGY
Optics-assisted enhanced sensing at radio frequencies in an optoelectromechanical system	Eshaqi-Sani, Najmeh et al.	PHYSICAL REVIEW APPLIED

- Mechanical characterisation of a membrane with an on-chip loss shield in a cryogenic environment *Appl. Phys. Lett. 126, 174002 (2025)*

- Large amplitude mechanical coherent states and detection of weak nonlinearities in cavity optomechanics *– Quantum Science and Technologies Accepted (2025)*