Thermal kinetic inductance detectors for soft X-ray spectroscopy

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Frontier Detectors for Frontier Physics
14th Pisa meeting on advanced detectors

Overview

Superconducting microwave microresonators are low temperature detectors (LTDs) suitable for large-scale frequency domain multiplexing readout. A promising approach consists in operating the resonators in quasi-thermal equilibrium mode: the resonator acts as a thermometer sensing the temperature rise of an absorbing material caused by an energy release. Our aim is to develop such detectors to perform spectroscopy in the keV range, with a possible future application to a next generation experiment aimed at directly measuring the neutrino mass. Still, the best configuration in terms of detector design and material must be found. Resonators made of several Ti/TiN multilayer films, which is a high kinetic inductance superconducting material previously developed by our group, were recently produced. The resonators are deposited onto a silicon slab and the sensitive area, thermally coupled to a gold absorber, is kept suspended by means of a SiNx membrane. In this way we plan to exploit the excellent energy resolution of LTDs combined with the simple multiplexing scheme of the resonators. In this contribution we present the devices along with our project, with its status and perspectives.

Thermal Mode

The responsivity of a MKID is related to the $d\sigma/dN_{qp}$, where σ is the complex conductivity;

Two possible ways:

J. Gao et al.,
J. Low Temp. Phys.
151 (2008) 557

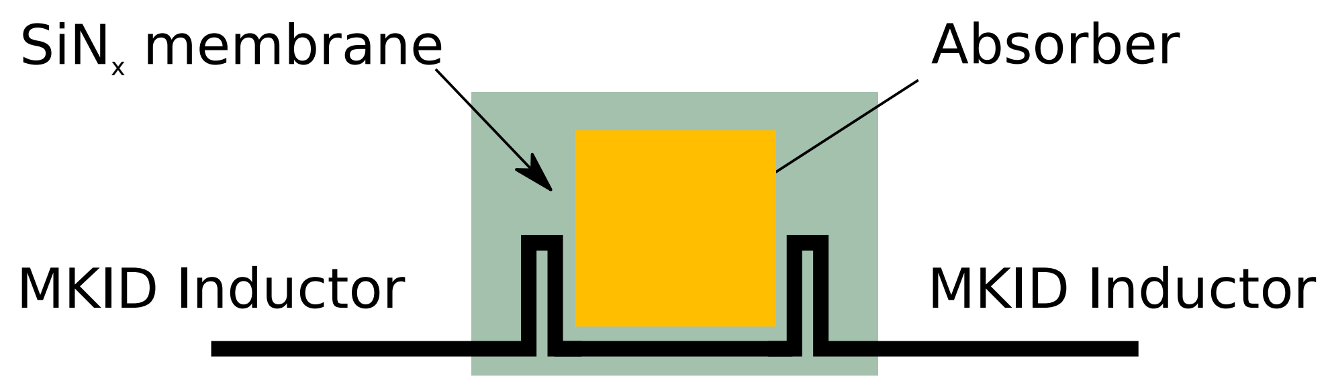
- In non-equilibrium mode (**athermal mode**) the quasiparticle excess $d\sigma/dn_{qp}$ is due to a phonon-mediated quasiparticle breaking caused by an external photon
- In thermal equilibrium mode (**thermal mode**) an equivalent increase of quasiparticle population can be generated by a temperature rise

In **Thermal Mode** the X-ray detection is possible by using an absorber thermally coupled to the inductive part and suspended by means if a Si_2N_3 membrane.

Energy resolution : theoretically limited only by thermodynamic fluctuations across the thermal weak link:

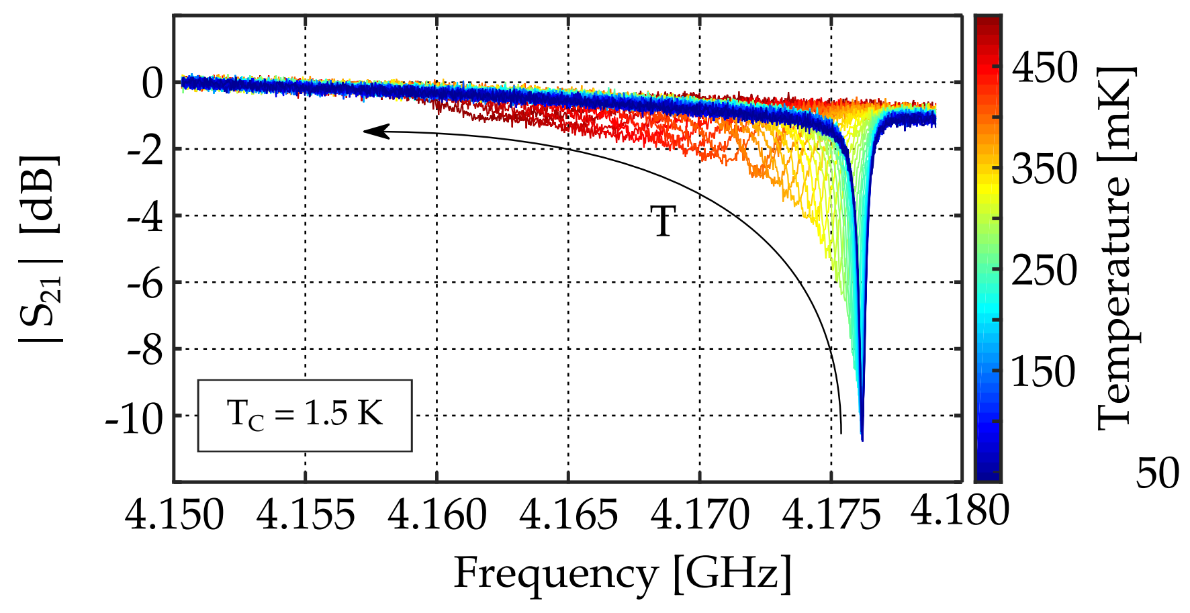
$$\Delta E \simeq \xi\sqrt{k_B T^2 C}$$

- The temperature rise due to a X-ray is detected by exploiting an absorber thermally coupled to the microresonator inductor.

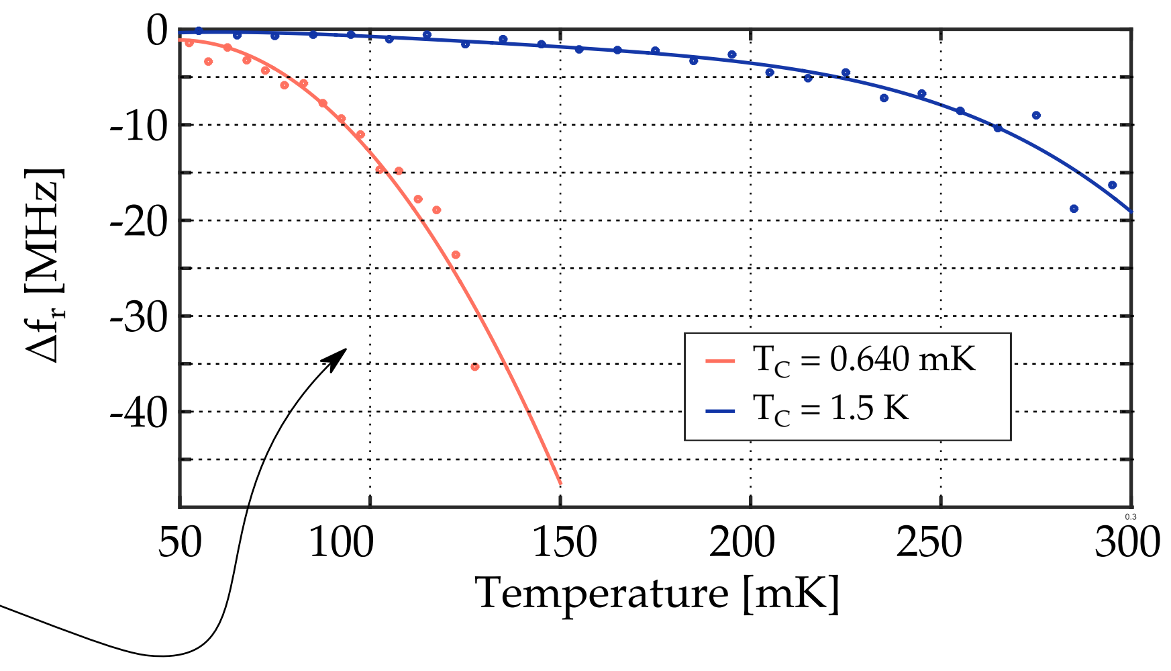


- Technique demonstrated in 2015 with a prelimiray resolution of 75 eV at 5.9 keV; *G. Ulbrich et al. Appl. Phys. Lett. 106 (2015) 251103*
- Better performaces achievable: 1) by finding the optimal tradeoff between the frequency response and the critical temperature, 2) by optimizing thermal design;
- The variation of the resonant frequency as a function of the temperature is steeper with lower critical temperatures.

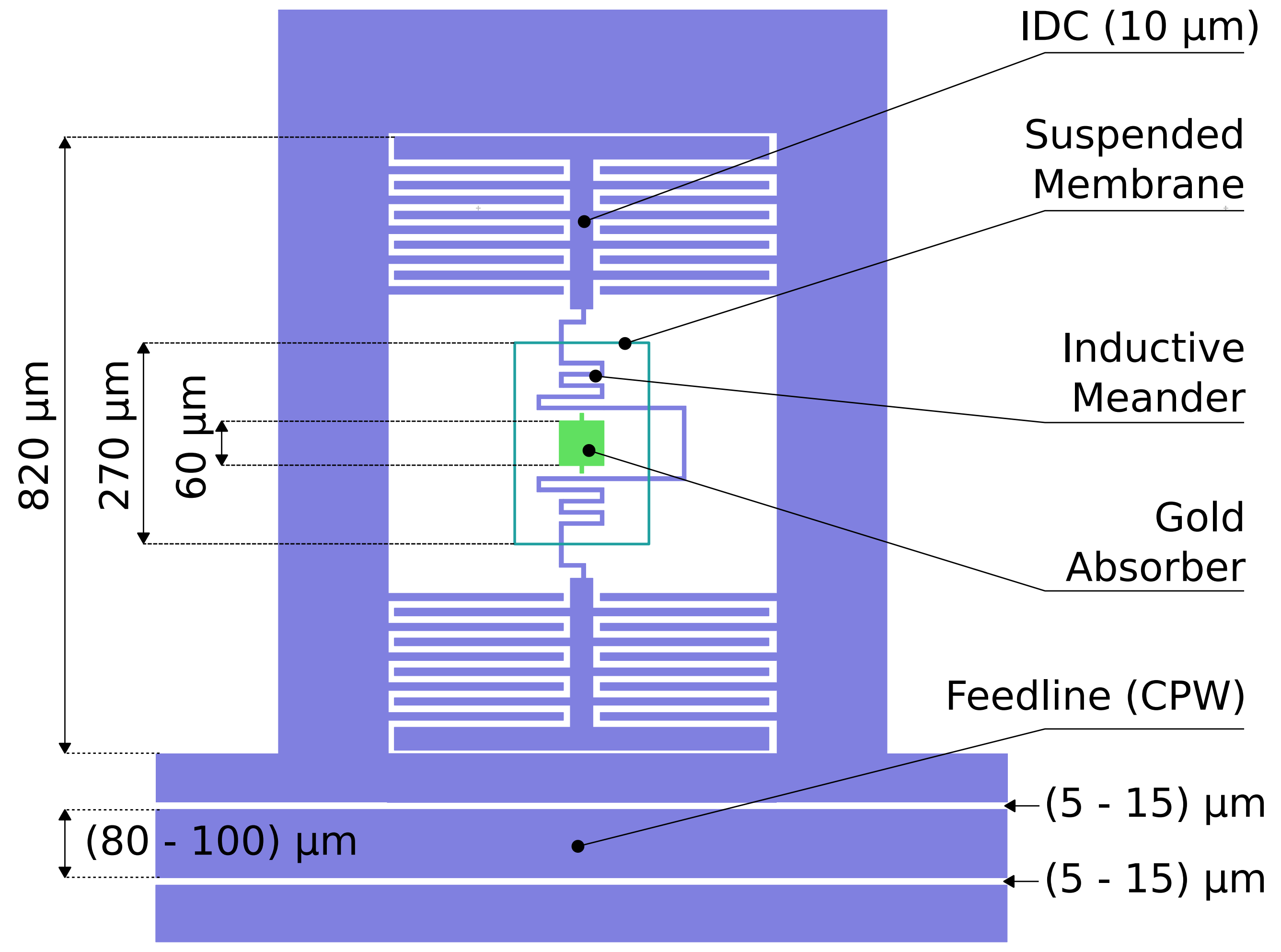
Resonance shift as a function of the temperature



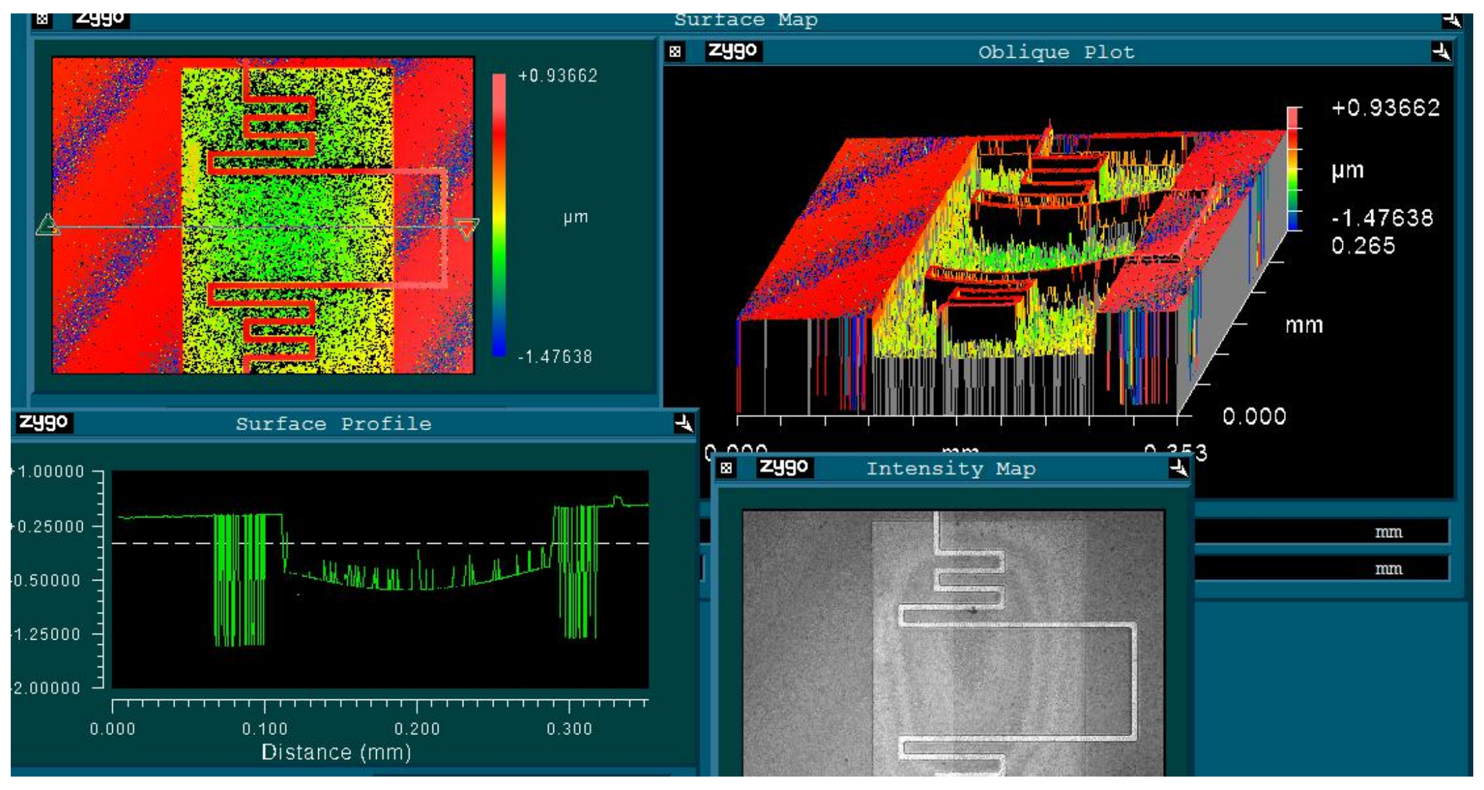
A Giachero et al.
J. Low. Temp. Phys. 184 (2016) 123



Microresonators Design



- Simmetric lumped element design with two interdigitated capacitors (IDC) connected by a meander that works as inductor *M. Faverzani, et al. J. Low Temp. Phys. 167 (2012) 1041*
- Resonator capacitively coupled to a coplanar waveguide (CPW) used as feedline and for the readout
- The spacing and width of the conductors of the IDC are optimized to minimize the TLS noise
- Different resonator configurations, combination of different kinetic impedances (L_k = 12, 20, 30 pH/sq) and nominal quality factors ($Q = 5 \cdot 10^3, 15 \cdot 10^3, 40 \cdot 10^3$)
- Gold absorbers 2 µm thick with different geometries: 60 × 60 µm^2, 80 × 40 µm^2, and 60 × 60 µm^2 with "fingers" (meant to increase the thermal coupling between the absorber and the inductor)
Absorber suspended on a SiN$_x$ membrane to provide a finite
- thermal reference toward the bath



- First prototypes with 4 microresonators for each combination of L_k and Q has been produced
- Profilometry shows good tensile properties of the membrane
- Resonant frequencies in the range from 4 to 6.5 GHz
- The best performing resonator configuration will be implemented in a larger array

Fabrication Process

- Superconducting films made by using multilayer Ti/TiN films composed by a superposition of bilayers Ti/TiN (proximity effect);
- The superconducting proximity effect in Ti/TIN multi-layer films allows to achive a target critical tempeturare T_c with a good reproducibility and uniformity in the range (0.1 - 4.5) K; *A Giachero et al. J. Low Temp. Phys. 176 (2014) 155*
- Three different families of superconducting film for three different critical temperatures ⇨ three different values of kinetic inductance;

Ti [nm]	TiN [nm]	N layers	Total thikness	Target T_C [K]	Target L_k [pH/□]
10	12	5	110	1.5	12
10	10	5	100	0.8	20
10	7	6	102	0.6	30

- Miscroresonators fabbricated on a 6″ double side polished 625 µm thick 100 oriented high resistive 5000 Ωcm p-type silicon wafers.
69 microresonator arrays per wafer ⇨ in total 3 × 69 = 207 arrays
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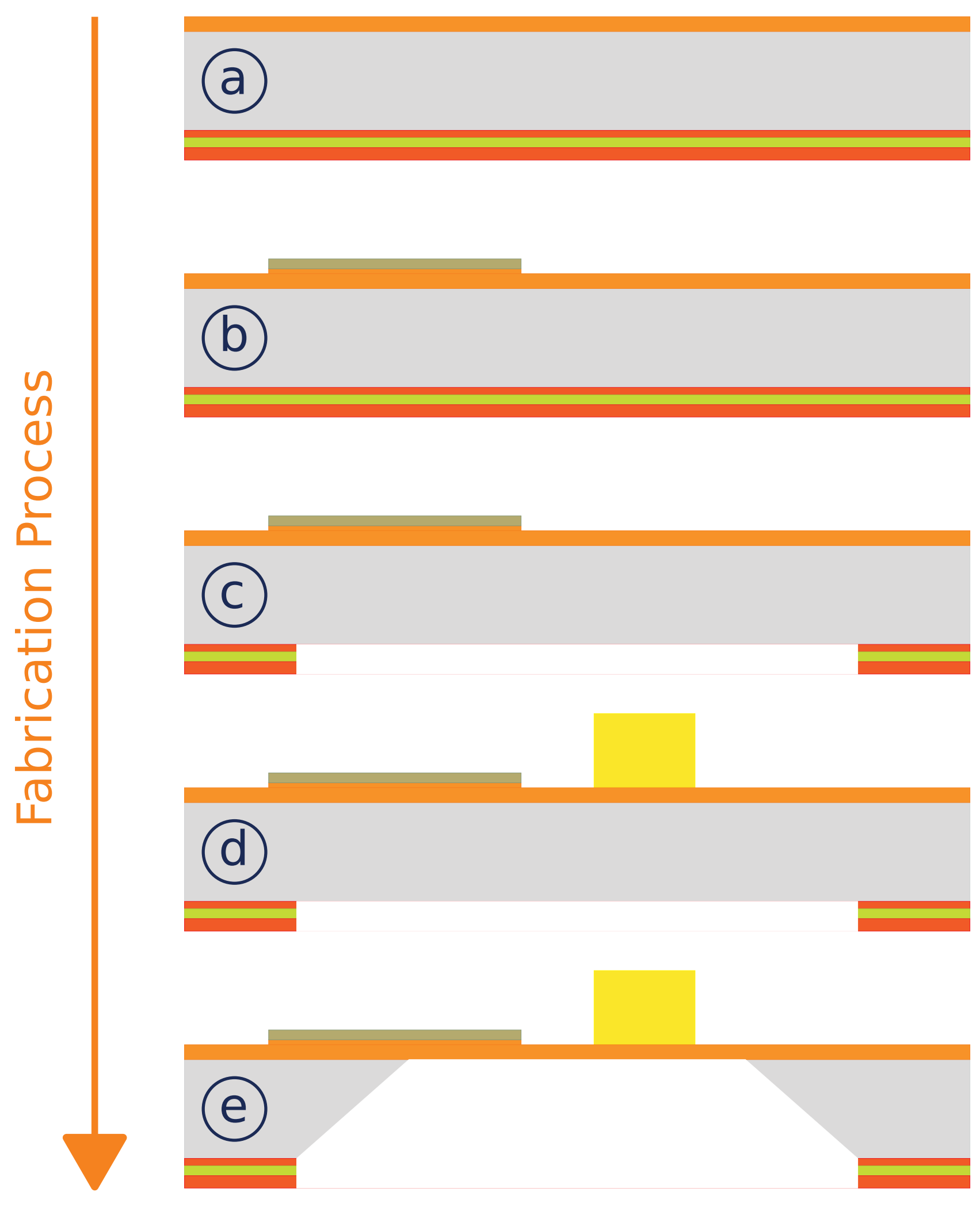

ⓐ Deposition of a composite hard mask consisting in 300 nm of thermal oxide, 150 nm of stoichiometric silicon nitride followed by 300 nm of a medium temperature oxide obtained by vapour deposition of tetramethyl orthosilicate (TEOS) on the wafer backside. On the wafer front side a 725 nm thick low stress silicon nitride is deposited by Plasma Enhanced CVD;

ⓑ Ti/TiN bilayers are deposited by sputtering for a total thickness of around 100 nm at 350 °C in which the micro resonators are defined and etched;

ⓒ Second lithography step the etch window for the bulk micromachining is defend and opened in the hard mask on the wafer backside;

ⓓ After this a thin titanium Ti/Au seed layer is deposited on the front side and with a 10 µm thick photoresist a mask is defined for the galvanic deposition of the 2 µm thick gold absorber;

ⓔ Removal of the silicon under the silicon nitride membrane by bulk silicon etching in a tetra methyl ammonium hydroxide: water solution (TMAH).