Development of Thermal Kinetic Inductance Detectors suitable for X-ray spectroscopy

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LTD17
July 17-21, 2017
Kurume, Fukuoka, Japan

Overview

The aim of the project is to implement MKIDs sensors working in thermal quasi-equilibrium mode to detect X-ray photons as pure calorimeters. The thermal mode is a variation on the MKID classical way of operation that has generated interest in recent years. TKIDs can offer the MKIDs inherent multiplexibility in the frequency domain, a high spatial resolution comparable with CCDs, and an energy resolution theoretically limited only by the thermodynamic fluctuations across the thermal weak links. Microresonators are built in Ti/TiN multilayer technology with the inductive part thermally coupled with a metal absorber on a suspended SiN membrane, to avoid escape of phonons from the film to the substrate. The mid-term goal is to optimize the single pixel design in term of superconducting critical temperatures, internal quality factors, kinetic inductance and spectral energy resolution. The final goal is to realize a demonstrator array for a next generation thousand pixels X-ray spectrometer.

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

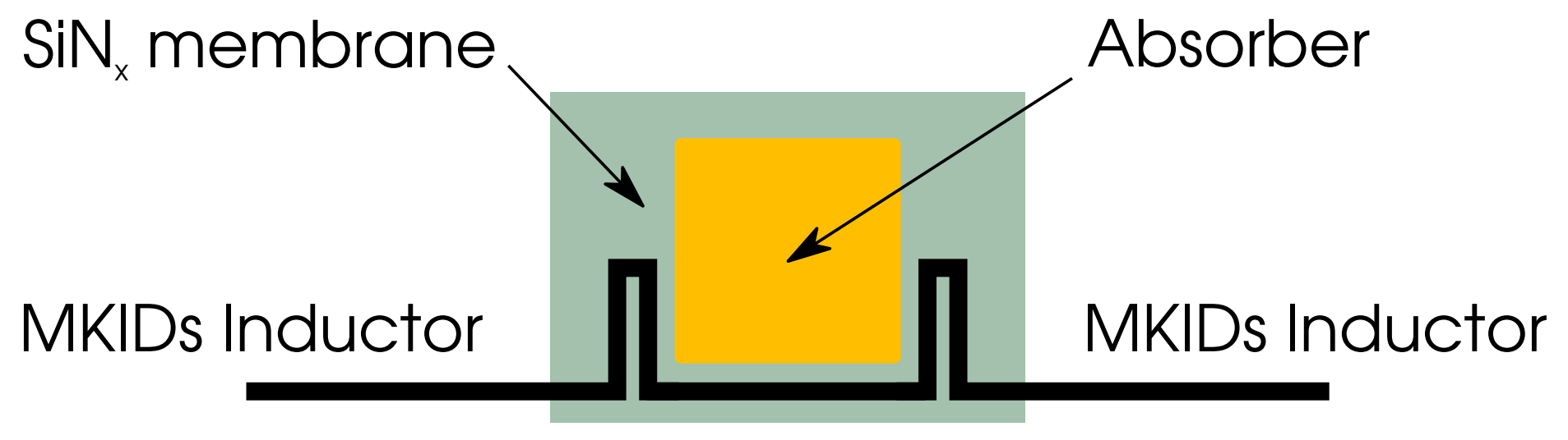
- In non-equilibrium mode (**athermal mode**) the excess quasiparticles $d\sigma/dn_{qp}$ is due to a non mediate quasiparticle breaking by an external photon
- In thermal equilibrium mode (**thermal mode**) an equivalent increase of quasiparticle population can be generated by a temperature change

In **Thermal Mode** the X-ray detection is possible by using an absorber thermally coupled with 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:

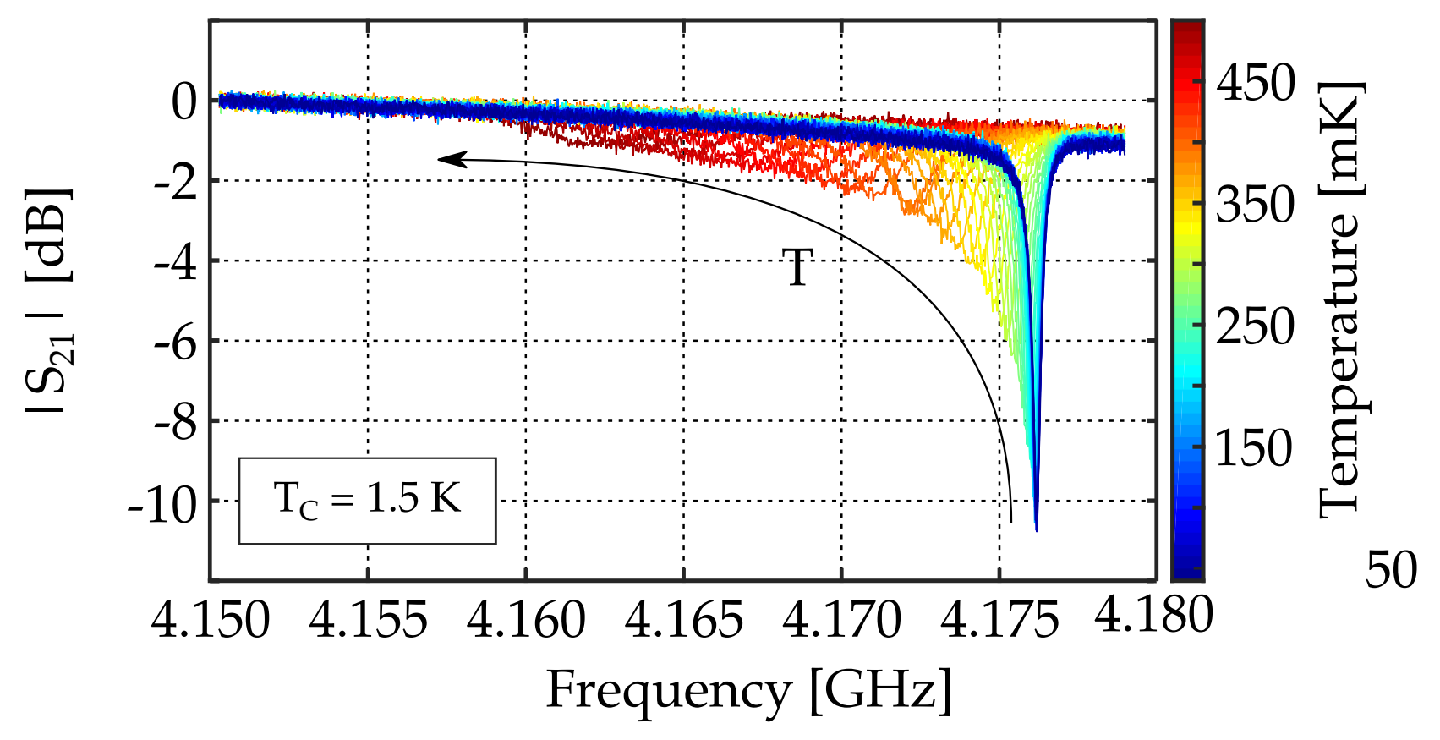
$$\Delta E \simeq \xi\sqrt{k_B T^2 C}$$

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

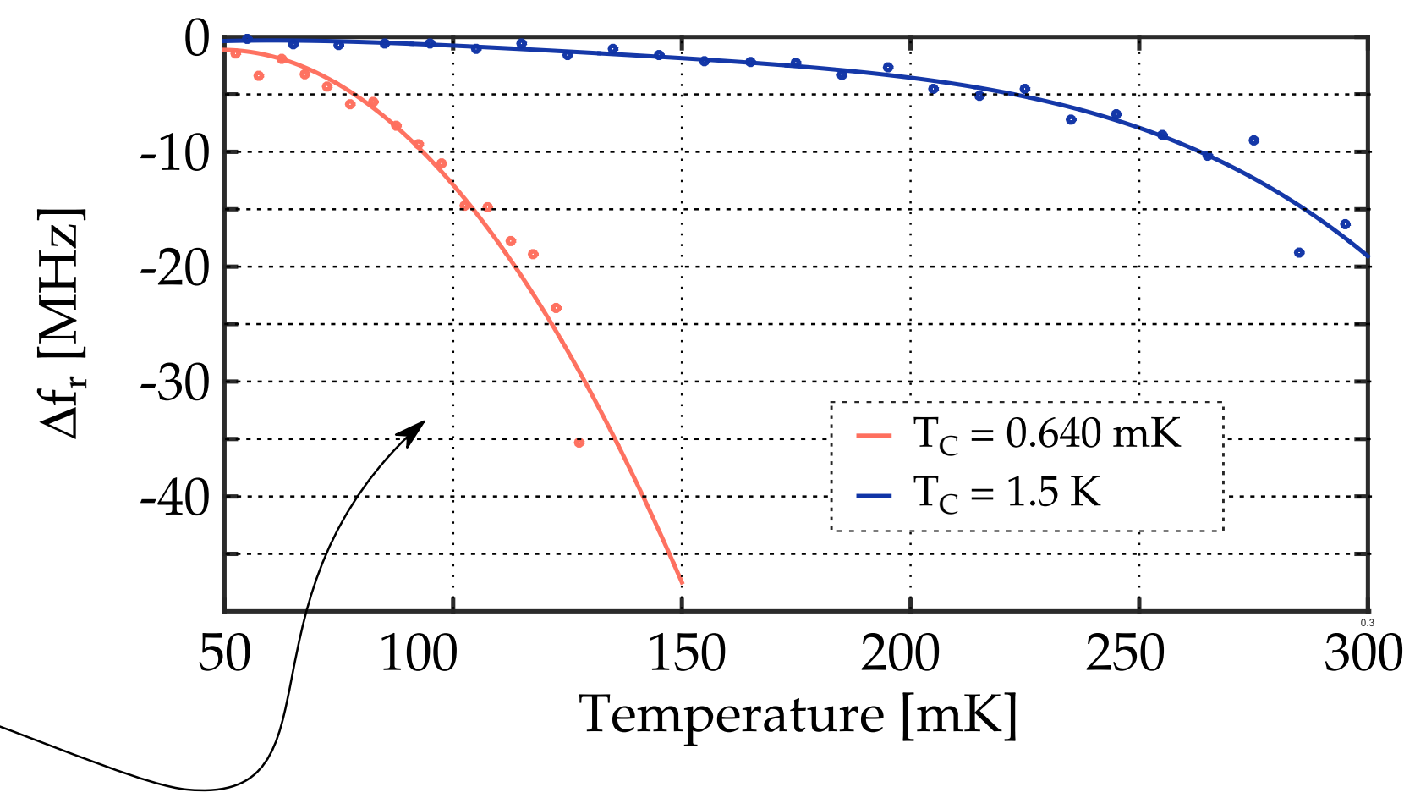


- Technique demonstrated in 2015 with a prelimiray resolution of 75 eV at 5.9 keV; *G. Ulbrich et al. Appl. Phys. Lett. 106 (2015) 251103*
- Better performaces achievable: 1) by finding the optimal tradeoff between the frequency response and the critical temperature, 2) by optimizing thermal design;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

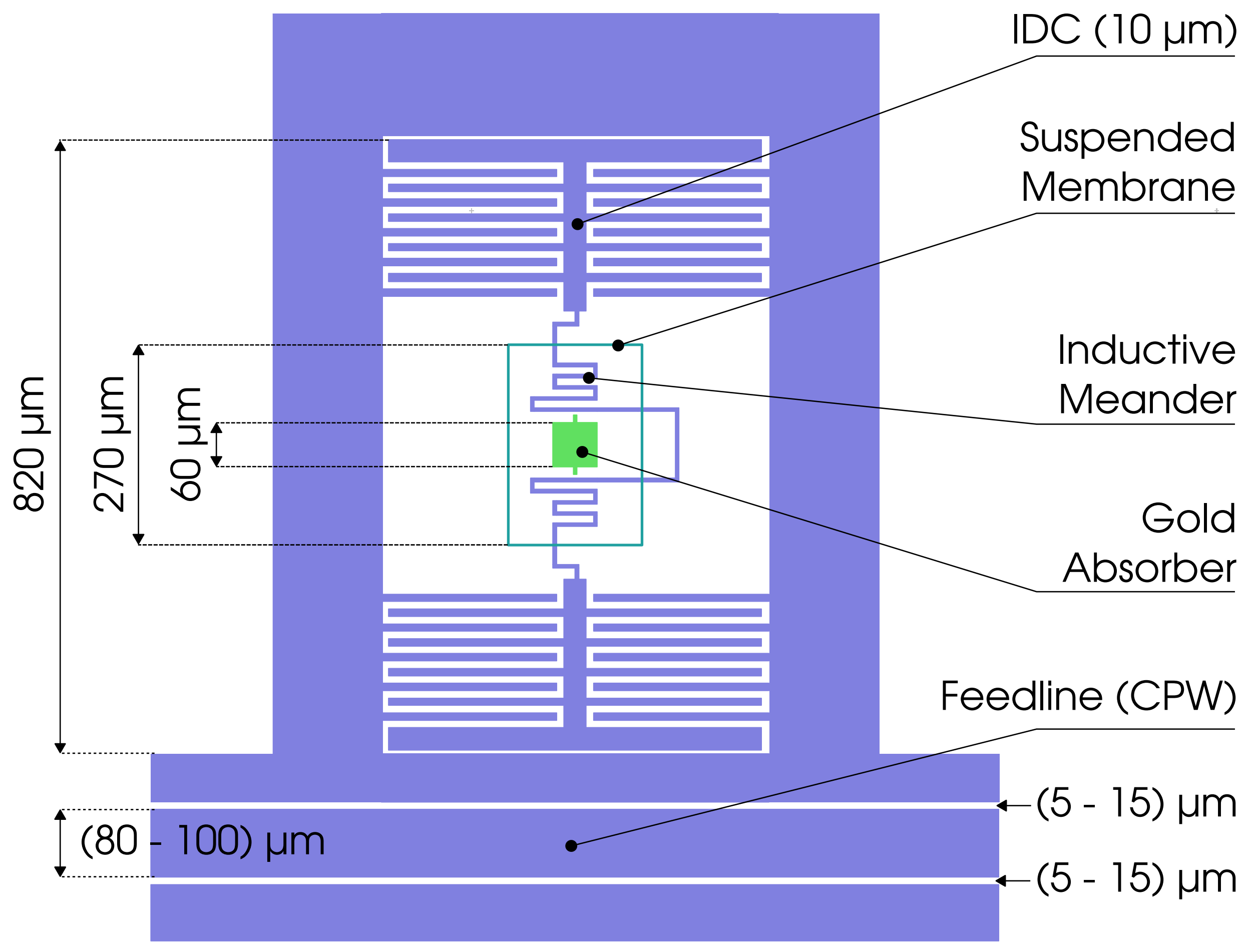
Resonance shift as a function of the temperature



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

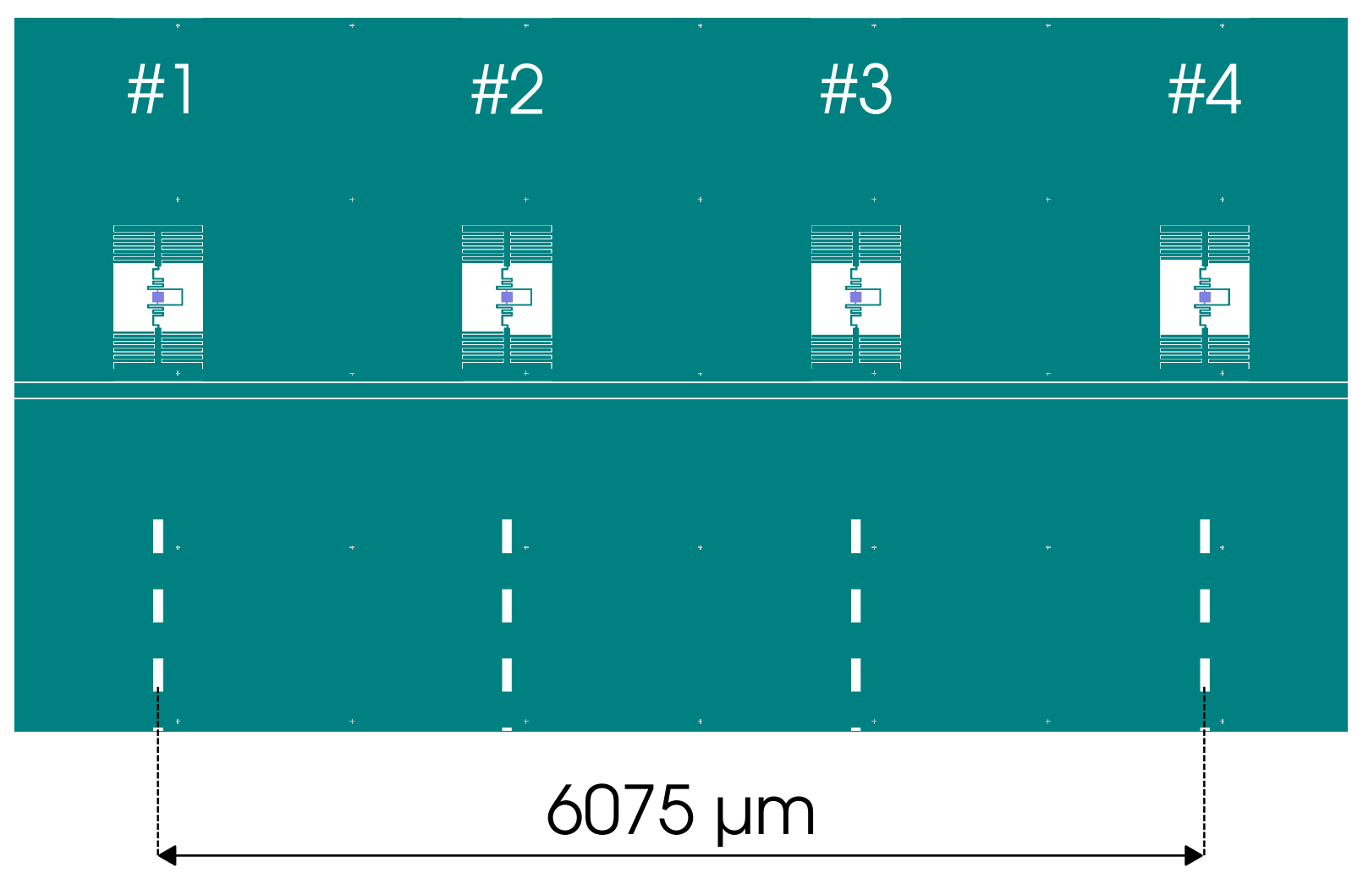


Microresonators Design



- Simmetric lumped element design form with two interdigitated capacitors (IDC) connected with 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 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 µm², 80 × 40 µm², and 60 × 60 µm² with finger (to increase the thermal coupling between the absorber and the inductor).
- Absorber suspended on a SiN$_x$ membrane to miminize phonon exchange and to provide a finite thermal conductance to the bath.

Zoom around the microresonators



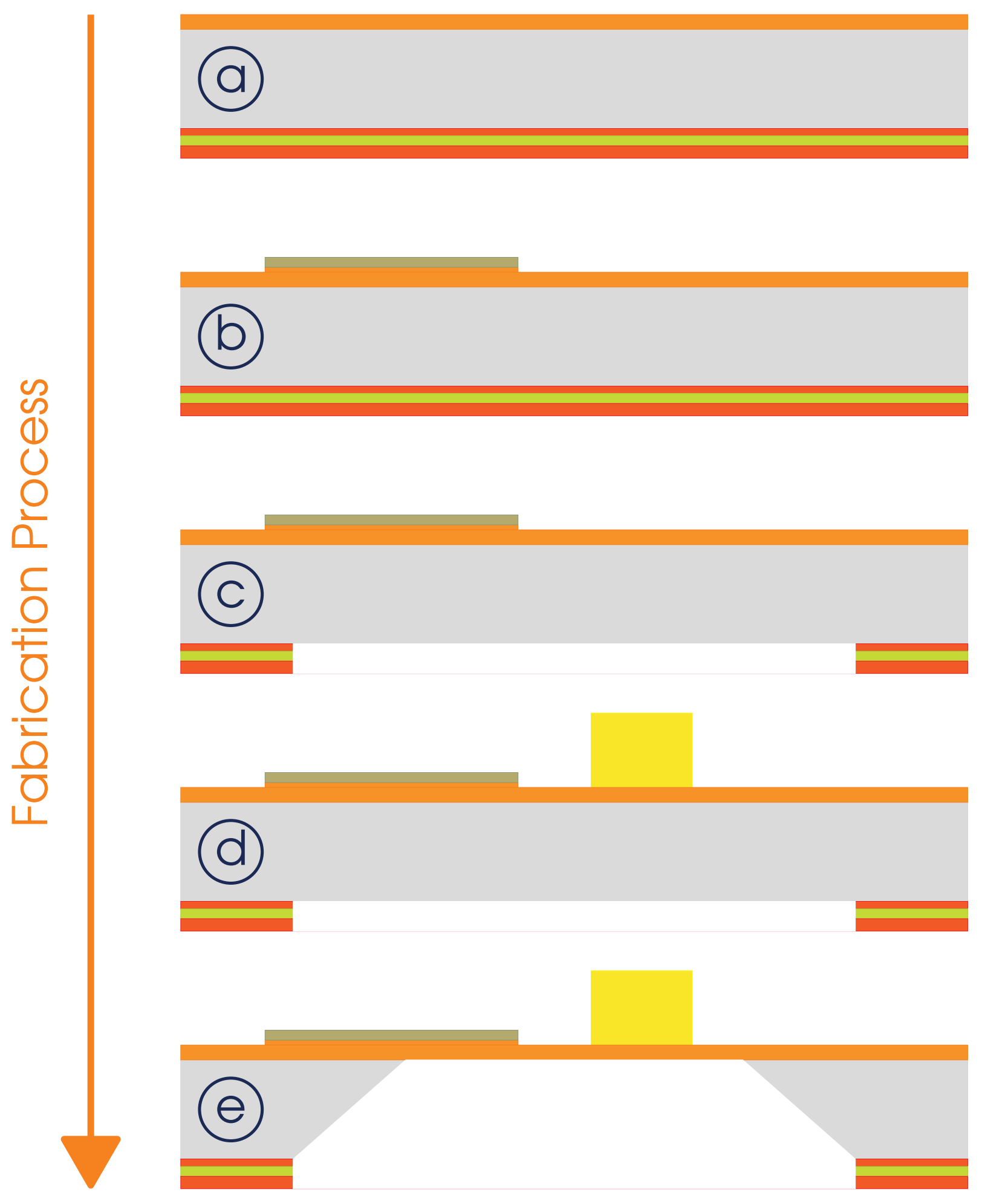
- First prototypes with 4 × 1 microresonators for each combination of kinetic inductance and quality factor. Total chip size: 19800 × 7800 µm².
- Resonant frequencies in the range from 4 to 6.5 GHz
- The best performing resonator configuration will be implemented in a larger array;

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



ⓐ 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).

Current Status

- Microresonator arrays designed and fully simulated;
- Wafers currently in production at the FBK MicroSystems Technology (MST) Research Unit
- ROACH2-based multiplexing and readout system otpimized for TKIDs.

Future Plans

- Deep characterization of the produced microresonators, measuring all the relevant parameters;
- Dedicated measurements to understand the position dependency in the absorber;
- Best performing pixels will be optimized and implemented in a larger array;