Thermal kinetic inductance detectors for soft X-ray spectroscopy

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Fluctuations across the thermal weak link:

- In non-equilibrium mode (athermal mode) the quasiparticle excess d\(\sigma/\sigma_{qp}\) 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 of a SiN\(_x\) membrane.

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

\[\Delta T \approx L_{eq} \sigma_{QP}/T^2\]

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

\[\text{SiN, membrane} \quad \text{Absorber} \quad \text{MKID Inductor}\]

- Technique demonstrated in 2015 with a preliminary resolution of 75 eV at 5.9 keV;
- Better performances 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.

Microresonators Design

- Symmetric lumped element design with two interdigitated capacitors (IDC) connected by a meander that works as inductor;
- 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 (\(L_a = 12, 20, 30 \text{ pH}\)) and nominal quality factors (\(Q = 5 \times 10^4, 15 \times 10^4, 40 \times 10^4\));
- Gold absorbers 2 \(\mu\)m thick with different geometries: 60 \(\times\) 60 \(\mu\)m\(^2\), 80 \(\times\) 40 \(\mu\)m\(^2\), and 60 \(\times\) 60 \(\mu\)m\(^2\) 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.

Fabrication Process

- Superconducting films made by using multilayer Ti/TaN films composed by a superposition of bilayers Ti/TaN (proximity effect);
- The superconducting proximity effect in Ti/TaN multi-layer films allows to achieve a target critical temperature \(T_c\) with a good reproducibility and uniformity in the range \((0.1 \ldots 4.5)\) K;
- Three different families of superconducting film for three different critical temperatures \(T_c\) at three different values of kinetic inductance;

<table>
<thead>
<tr>
<th>Ti (mm)</th>
<th>TiN (nm)</th>
<th>L (\text{um})</th>
<th>(T_c) (K)</th>
<th>(\Delta T_{in}) (mK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>10</td>
<td>12</td>
<td>0.6</td>
<td>20</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>10</td>
<td>0.8</td>
<td>20</td>
</tr>
<tr>
<td>10</td>
<td>7</td>
<td>10</td>
<td>0.6</td>
<td>30</td>
</tr>
</tbody>
</table>

- Microresonators fabricated on a 6" double side polished 625 \(\mu\)m thick 100 oriented high resistive 5000 Gcm p-type silicon wafers.
- 69 microresonator arrays per wafer = in total \(3 \times 69 = 207\) 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 oxide membrane is defined;
- Deposition of tetramethyl orthosilicate (TEOS) on the wafer backside; on the wafer front side a 725 nm thick low stress silicon nitride membrane is defined;
- Removal of the silicon under the silicon nitride membrane by bulk silicon etching in a tetra methyl ammonium hydroxide: water solution (TMAH).

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/TaN 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 SiN\(_x\) 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.