Superconducting Microresonator Detectors for Neutrino Physics in Milano

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Abstract.

Superconducting microwave microresonators are low temperature detectors compatible with large-scale multiplexed frequency domain readout. Our aim is to adapt and further advance the technology of microresonator detectors to develop new devices applied to the problem of measuring the neutrino mass. More specifically, we aim to develop detector arrays which can be applied to the calorimetric measurement of the energy spectra of $^{163}$Ho EC decay ($Q \sim 2$-3 keV) for a direct measurement of the neutrino mass. In order to achieve this goal, a study aimed to the selection of the best design and material for the detectors is required. A recent advance in microwave microresonator technology was the discovery that some metal nitrides, such as TiN, possess properties consistent with very high detector sensitivity. In this contribution, our progress on the design and test of Ti/TiN multilayer films is presented. We report measurements made on stoichiometric TiN, sub-stoichiometric TiN and multilayer Ti/TiN films including the critical temperature, the gap parameter and the quasi-particle recombination time extrapolated from $\sim$keV X-ray pulses.

1. Introduction

The determination of the neutrino mass is still an open question in particle physics. Direct neutrino mass measurements, performed by analyzing the kinematics of suitable weak decays, are able to tackle this problem. Exploiting only energy and momentum conservation, they are essentially free of theoretical assumptions about neutrino properties and are truly model-independent. These experiments look for a tiny deformation of the beta spectrum near the end point energy due to a non vanishing neutrino mass. The calorimetric technique, where the $\beta$ source is embedded in the detectors, is a promising tool since the entire energy except the fraction carried away by neutrinos is measured. This approach eliminates the systematic effects connected with the use of an external source as in a $\beta$ spectrometer. A disadvantage is that the isotope used in calorimetric measurements must be characterized by a low end point energy $Q$ in order to allow a trade off between keeping the isotope activity low to minimize pile-up events and still achieving a high statistical sensitivity. An appealing isotope applicable to neutrino mass measurement could be the $^{163}$Ho ($Q \sim 2.5$ keV), which decays via electron capture EC to $^{163}$Dy.
with a half-life of about 4570 y. The capture is only allowed from the M shell or higher. One of the methods to estimate the neutrino mass from the $^{163}$Ho consists in studying the end-point of the total absorption spectrum as proposed by Rujula and Lusignoli in 1982 [1]. The absorption spectrum is made up of peaks with Breit-Wigner shapes and it ends at $Q - m_{\nu}$. In order to obtain a sub-eV sensitivity on neutrino mass, it would be necessary to have a large number of detectors multiplexed ($\sim 10^4$) with a good time response ($\sim \mu$s) and a good energy resolution ($\sim$ eV @ keV).

Our aim is to develop arrays of athermal micro-resonator detectors for the electron capture end point measurement of the neutrino mass using $^{163}$Ho as source material [2, 3]. Currently, a study aimed to select the best material and the best design for the detectors is in progress. In this contribution the current progress on the design and test of Ti/TiN multilayer film is presented. Furthermore, a comparison between the characteristic parameters (i.e. critical temperature, gap parameter, quasiparticle recombination time) of films made of stoichiometric, sub-stoichiometric TiN and Ti/TiN multilayer films is reported. The sub-stoichiometric was provided by Jet Propulsion Laboratory while the stoichiometric and multilayer films by Fondazione Bruno Kessler in Trento.

2. Detector layout

Our array is composed by 16 individual detectors (lumped-element resonators) with resonance frequencies distributed from 3 to 6 GHz and with a variety of coupling quality factors. Their layout consists of two interdigital capacitors (IDC) connected with a coplanar strips (CPS) transmission line that works as an inductor. Each resonator is capacitively coupled on one side to a coplanar waveguide (CPW) line that is used for the readout. The strength of the coupling, which set the coupling quality factor $Q_c$, is determined by the width of the gap between the CPW line and the resonator. The spacing between the IDC finger is 10 or 30 $\mu$m. This large spacing is intended to reduce the two-level system (TLS) noise associated with amorphous dielectric layers at surfaces. For more details see [2].

3. Film production

Our goal is to produce films with a $T_c$ in the range 1÷1.5 K in order to have a low energy gap and long quasi-particle recombination time (i.e. low generation-recombination noise). Titanium Nitride (TiN) is a well suited for the production of MKIDs. Indeed TiN resonators show very high quality factors and large ratios of kinetic to magnetic inductance. Furthermore, by changing the amount of Nitrogen added to the Titanium film it is possible to tune the critical temperature $T_c$ [4] in the range between 0 and 5 K. The $T_c$ lowering occurs for a narrow range of nitrogen concentration and requires a very precise control of the nitrogen incorporation. An alternative that we preferred deals with Ti/TiN multilayer [5]. The basic idea is to fabricate films composed by a sequence of pure Titanium and stoichiometric TiN layers. Indeed, it is known that the $T_c$ of a superconducting material can be reduced by the superposition of a normal metal or a metal with a superconductive transition at lower temperature [6, 7]. In this configuration the Cooper pairs leak into the normal metal, consequentially the pair density in the superconducting metal is reduced as well as the $T_c$. The magnitude of this effect depends on the thickness of the two layers. By adjusting these thickness one is able to tune the $T_c$ between the transition temperature of Ti (0.4 K) and TiN (5 K).

The Ti/TiN multilayer have been produced by the superposition of layers Ti/TiN with Ti at the bottom interface and TiN on the top. The maximum number of stacked layers is 8. The films have been sputtered on high resistance Silicon wafers, which had been cleaned and etched with hydrofluoric acid (HF) to remove the native oxide. The DC 4-wire measurement of the electrical resistance as function of temperature was performed at the Cryogenic Laboratory of the University of Trento. The results have shown that it has been possible to tune the $T_c$
between 0.5 and 4.6 K by properly choosing the Ti thickness in the (0 ÷ 15) nm range, and the TiN thickness in the (7 ÷ 100) nm range. The \( T_c \) can be lowered by reducing the TiN thickness with fixed thickness of Ti or by keeping fixed the TiN thickness and increasing that of Ti. In this latter case the \( T_c \) is more sensitive to layer thickness variations in the (5 ÷ 10) nm range and it is nearly stable for Ti thickness < 5 nm and > 10 nm. The produced Ti/TiN multilayers have shown a high uniformity and high quality factor [8].

4. Device characterization

Microwave measurements were performed to determine the characteristic parameters of the resonators made of stoichiometric, sub-stoichiometric TiN and Ti/TiN multilayer films. The critical temperature has been evaluated by measuring the amplitude of the RF signal transmitted through the resonator feed line as a function of the temperature. The energy gap parameter has been calculated by measuring the internal Qs of the resonators vs temperature (figure 1) and fitting to the relation:

\[
\frac{1}{Q(T)} = \frac{1}{Q(0)} + \frac{\alpha \sigma_1(T)}{2\sigma_2(T)}
\]

where the conductance depends (in the limit \( k_B T \ll \Delta(0) \), \( h \nu \ll \Delta(0) \)) on the gap parameter \( \Delta \) as follow [9]:

\[
\frac{\sigma_1}{\sigma_n} \approx \frac{4\Delta(T)}{h \omega} \exp\left(-\frac{\Delta(0)}{k_B T}\right) K_0\left(\frac{h \omega}{2k_B T}\right) \sinh\left(\frac{h \omega}{2k_B T}\right)
\]

\[
\frac{\sigma_2}{\sigma_n} \approx \frac{\pi \Delta(T)}{h \omega} \left[1 - 2e^{-\frac{\Delta(0)}{k_B T}}\exp\left(-\frac{h \omega}{2k_B T}\right) I_0\left(\frac{h \omega}{2k_B T}\right)\right],
\]

where \( I_0 \) and \( K_0 \) are modified Bessel functions, \( \sigma_n \) is the normal state resistance just above \( T_c \).

![Figure 1](image.png)

**Figure 1.** Example of the gap measurement for a multilayer film: it is possible to see how the resonant frequency and the Q of one single resonance decrease while the temperature increase.

The measured values for four different films are reported in the table 1.

5. Quasiparticle recombination time and energy spectra

Tests were performed radiating the detectors with two calibration sources (\(^{55}\)Fe, \( \sim \) 6 keV; fluorescence of Al, \( \sim \) 1.5 keV) to extrapolate the quasi-particle lifetime at different temperatures...
Table 1. Critical temperature, gap parameter and Qs obtained for our films. The sub-stoichiometric was provided by Jet Propulsion Laboratory while the stoichiometric and multilayer films by Fondazione Bruno Kessler in Trento. In the table it is also listed the quasi-particle recombination time at 25 mK.

| Film                        | $T_c$(K) | $\Delta$(meV) | $Q_s$ | $\tau_{fast}$(µs) | $\tau_{slow}$(µs) |
|-----------------------------|---------|---------------|-------|-------------------|-------------------|
| Stoichiometric TiN         | 4.6     | 0.8           | $10^5$| –                 | 8                 |
| Sub-stoichiometric TiN     | 2.5     | 0.37          | $10^6$| 25                | 145               |
| Ti(10nm)/TiN(15nm) 8 layers | 1.6     | 0.26          | $10^5$| –                 | –                 |
| Ti(10nm)/TiN(12nm) 8 layers | 1.2     | 0.17          | $5\cdot10^4$ | 31           | 105               |

and to build the first energy spectrum. The observed pulses showed several different behaviors: slower pulses, with a single exponential decay constant, very fast pulses decaying faster than exponential, and pulses with two exponential decay times. We interpret the slow component as the quasi-particle recombination time and the fast component as a result of a recombination of quasi-particles due to a local excess of quasi-particles. The results are listed in table 1.

Unfortunately, in the energy spectra acquired no peaks were observed. This feature could be explained by an escape of phonons from the detector to the substrate. Besides, since the large majority of X-rays are absorbed in the substrate ($\sim$ 90%), a response to the phonons thereby produced could induce an energy degraded response of the detector. Finally, given the slow diffusivity of the TiN, a transition of the superconductor into normal metal state, caused by a local excess of quasi-particles, is also possible. To obtain an energy-resolving resonator, we are considering 3 different future upgrades: resonators with the inductor line suspended from the substrate to prevent the exchange of phonons between the film and the substrate; resonators with the inductor coupled to a higher-gap absorber with a faster diffusion to prevent the recombination of the quasi-particles before they diffuse; and ultimately, thermal devices.

6. Conclusion

Ti/TiN multilayer films suitable for a next generation of neutrino experiments are produced. The characteristic parameters, such as the $T_c$, the gap parameter and the quasi-particle lifetime of different TiN superconducting films have been measured. The energy spectra acquired have not yet shown well defined peaks, so new resonators are under investigation.

Acknowledgments

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