High-sensitivity Kinetic Inductance Detectors for CALDER

A. D’Addabbo ‡, F. Bellini 2,3, L. Cardani 3, N. Casali 3, M. G. Castellano 4, I. Colantoni 4, C. Cosmelli 2,3, A. Cruciani 3, S. Di Domizio 5,6, M. Martinez 2,3, C. Tomei 3, M. Vignati 3

1 INFN - Laboratori Nazionali del Gran Sasso (LNGS), Via Giovanni Acitelli 22, 67010, Assergi (AQ) - Italy
2 Dipartimento di Fisica - Sapienza Università di Roma, Piazzale Aldo Moro 2, 00185, Roma - Italy
3 INFN - Sezione di Roma, Piazzale Aldo Moro 2, 00185, Roma - Italy
4 Istituto di Fotonica e Nanotecnologie - CNR, Via Cineto Romano 42, 00156, Roma - Italy
5 Dipartimento di Fisica - Università degli Studi di Genova, Via Dodecaneso 33, 16146, Genova - Italy
6 INFN - Sezione di Genova, Via Dodecaneso 33, 16146, Genova - Italy

March 2017

Abstract. Providing a background discrimination tool is crucial for enhancing the sensitivity of next-generation experiments searching for neutrinoless double-beta decay. The development of high-sensitivity (< 20 eV RMS) cryogenic light detectors allows simultaneous read-out of the light and heat signals and enables background suppression through particle identification. The Cryogenic wide-Area Light Detector with Excellent Resolution (CALDER) R&D already proved the potential of this technique using the phonon-mediated Kinetic Inductance Detectors (KIDs) approach. The first array prototype with 4 Aluminum KIDs on a 2 × 2 cm² Silicon substrate showed a baseline resolution of 154 ± 7 eV RMS. Improving the design and the readout of the resonator, the next CALDER prototype featured an energy resolution of 82 ± 4 eV, by sampling the same substrate with a single Aluminum KID.

‡ Author’s email: antonio.daddabbo@lngs.infn.it
1. Introduction

The next-generation ton-scale experiments searching for neutrinoless double beta decay must be sensitive to a Majorana neutrino mass as low as 10 meV. Among them, CUORE (Cryogenic Underground Observatory for Rare Events) [1] is an array of 988 TeO$_2$ bolometers currently in its detector commissioning phase at Laboratori Nazionali del Gran Sasso, in Italy. It features a five-years projected sensitivity of 50-130 meV at 90% C.L. The removal of the background from α radioactivity would push the experiment sensitivity in the Majorana neutrino mass signal region. This is possible by detecting the tiny amount of Cherenkov light emitted only by the β signal in coincidence with the heat release in a bolometer [2]. To match the requirements of next-generation experiments, the light detectors must feature energy resolution better than 20 eV RMS, large active area (tens of cm$^2$), and the possibility of operating about 1000 channels in a wide temperature range (5 to 20 mK) [3][4][5].

Among the proposed technologies, Kinetic Inductance Detectors (KIDs) stand out for their natural multiplexed read-out and excellent intrinsic energy resolution [6]. To overcome their poor active surface (~mm$^2$) KIDs can be coupled to a much wider insulating substrate: photons interacting in the substrate are converted into phonons and finally absorbed by KIDs [7][8].

The CALDER project [9] aims at developing a small prototype experiment consisting of TeO$_2$ bolometers coupled to new light detectors based on KIDs. The R&D is focused on the light detectors that could be implemented in a next-generation neutrinoless double-beta decay experiment.

2. Methods

The prototypes of light detectors developed by the CALDER collaboration consist in 300 to 380 µm thick, 2 × 2 cm$^2$ wide-resistivity Si(100) substrates sampled by one to four KID sensors, with a LEKID design [10]. The superconducting resonators are made with 40nm-thick or 60nm-thick Aluminum, patterned by electron beam lithography on a single film deposited using electron gun evaporator [11]. The detectors are design to feature high quality factors and to resonate at a small prototype experiment consisting of TeO$_2$ × 2 cm$^2$, 300 µm thick Si substrate, reached a combined baseline resolution of 154 ± 7 eV, and an overall efficiency of 18 ± 2%, remarkable for an indirect detection. In this design, the active area of the resonator was 2.4 mm$^2$, corresponding to a single KID absorption efficiency of 3.1% – 6.1%, depending on the position of the source.

We characterized the 4-pixel array with coupling quality factor (Q$_c$) values in the range of 6–35 × 10$^3$. The typical pulse shape shows rise time of 10-30 µs, which is determined by the athermal phonon propagation into the substrate, and decay time of 200-1000 µs, that is dominated by quasiparticle recombination time ($\tau_{qp}$). A typical value at the optimum bias power, i.e. the power where the SNR (Signal-to-Noise Ratio) of an optical signal is maximized, is $\tau_{qp}$ ~ 220 µs.

To improve the detector resolution, we tested a single Al KID design in order to avoid cross-talk or competition in absorbing phonons. The single KID was deposited on 2 × 2 cm$^2$, 380 µm thick, high resistivity (>10 kΩ · cm) Si(100) substrates. Then, in order to increase the signal, we first raised the quality factor Q of the resonator ($Q = Q_i + 1/\tau_{qp}$): Q$_c$ was raised up to $10^5$ by design, and we used a 60 nm thick film to ensure a high internal quality factor Q$_i$ (> 10$^6$). Then, we enlarged the active area of the KID from 2.4 mm$^2$, in order to increase the fraction of phonons that can be collected. A comparison of the improved design with the one described in [15] is shown in figure [1]. Finally, we developed a combined amplitude ($\delta A$) and phase ($\delta \phi$) analysis technique that allowed us to combine the $\delta A$ and $\delta \phi$ signals and maximize the SNR [16]. Thanks to these improvements, the single-
pixel design detector featured a KID efficiency up to 7.4% – 9.4%, and a noise baseline resolution of $\sigma_E = (82 \pm 4)$ eV, a factor 2 better than the previous 4-pixels prototype described in [15].

4. Discussion

Thanks to the high Q resonator, improved geometry and combined readout, we obtained a signal height about a factor 6 larger with respect to the ones obtained with previous prototype, both in $\delta A$ and $\delta \phi$. However, all the tested prototypes featured an excess low-frequency noise that can just partially be ascribed to Two Level System. We are currently investigating its origin. On the other hand, the amplitude noise is consistent with the amplifier temperature and much lower than the phase one. For this reason, even if the amplitude signals are $\sim$10 times smaller than the phase ones, the SNRs are similar and both actually concur to enhance the energy resolution.

5. Conclusions and perspectives

An improvement of detectors’ sensitivity by at least a factor 2.5 is still needed to reach the goal of the project. Looking at the resolution expected if the noise was dominated by the cold amplifier, $\sigma_{\text{amp}}$, as described in [9], further improvements in sensitivity can be obtained by using of lower critical temperature ($T_c$) superconductors and/or higher kinetic inductance content materials. We are currently studying several new superconducting material for our application [11] (non stoichiometric TiN [17], Ti-Al bi-layer [18] and Ti-TiN multilayer [19]) that could take advantage of both these factors.

By the end of 2017, we foresee to conclude the development to bring the energy resolution of the light detectors below 20 eV RMS. In early 2018, we expect to construct a demonstrator, made of a bolometric TeO$_2$ array at Laboratori Nazionali del Gran Sasso, instrumented with CALDERs light detectors.

References

[1] A. D’Addabbo et al., EPJ. Web Conf., In Press, arXiv:1612.04276 (2016)
[2] N. Casali et al., EPJ C 75, 12 (2015)
[3] D.R. Artusa et al., EPJ C 74, 3096 (2014)
[4] The CUPID Interest Group, arXiv:1504.03599 (2015)
[5] The CUPID Interest Group, arXiv:1504.03612 (2015)
[6] P. K. Day et al., Nature 425, 817 (2003)
[7] L. J. Swenson et al., Appl.Phys.Lett. 96, 263511 (2010)
[8] D.C. Moore, et al., Appl.Phys.Lett. 100, 232601 (2012)
[9] E.S. Battistelli et al., EPJ C 75, 353 (2015)
[10] S. Doyle et al., J. Low Temp. Phys. 151, 530 (2008)
[11] I. Colantoni et al., J. Low Temp. Phys., 184, 131 (2016)
[12] O. Bourrion et al., JINST 6, P06012 (2011)
[13] O. Bourrion et al., JINST 8, C12006 (2013)
[14] N. Casali et al., J. Low Temp. Phys. (2015)
[15] L. Cardani et al., Appl. Phys. Lett. 107, 093508 (2015)
[16] L. Cardani et al., Appl. Phys. Lett. 110, 033504 (2017)
[17] S. Ohya et al., Supercond. Sci. Technol. 27, 015009 (2014)
[18] A. Catalano et al., A&A, 580:A15 (2015)
[19] M.R. Vissers et al., Appl. Phys. Lett. 102, 232603 (2013)