Improvement of Contact‑Less KID Design Using Multilayered Al/Ti Material for Resonator

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Abstract

The necessity to increase exposure in rare event search experiments by maintaining a low energy threshold and a good energy resolution leads to segmented detectors as in EDELWEISS (Dark Matter), CUORE (0νββ) or Ricochet (CENNS) for example. However, the large number of sub-elements can dramatically increase the complexity of such detector arrays. In this work we report on our progress towards designing a flexible detector technology based on Kinetic Inductance Detector (KID) resonators evaporated on massive target crystals readout by a contact-less feedline. Providing that we achieve \(O(100)\) eV energy threshold, such approach could easily be scaled to tens of kilogram detector arrays thanks to the intrinsic multiplexing capability of KIDs. Using a 30 g silicon target absorber with Al/Ti multi layers for the KID resonator, we report a significant improvement of our detector response exhibiting a keV-scale energy resolution combined with the absence of position dependence on the event location. Indeed, compared to our previous work, we are now able to properly identify calibration lines from surface (20 keV X-rays) and bulk events (60 keV gamma rays). This significant improvement is an important step towards a better understanding of phonons and quasiparticles dynamics, which is pivotal in optimizing this technology.

Keywords  KID · Phonons · Quasiparticles · Resonator · Rare event searches
1 Motivations and Experimental Setup

Multiplexing approaches are widely explored to overcome issues related to the scaling up of solid state cryogenic detectors. Although KIDs, within the context of individual particle detection, are not at the same level of maturity as other sensing technologies, e.g. Ge-NTD (Neutron Transmuted Doped-Ge) or Transition Edge Sensor (TES), they have the benefit of being intrinsically easy to multiplex. Therefore, this work focuses on improving our KID-based detector design energy resolution for future applications in low-energy and rare event searches.

The proposed design discussed hereafter, called wifi-KID, has a feedline which is not on the same substrate as the resonator. Though with a different technical implementation, this proposed design has a similar approach as what has been done in [3] since both have a vacuum coupling between the feedline and the absorber. The spacing between the resonator, already presented in our first wifi-KID study [5], and the feedline is roughly 300 μm. The resonator is evaporated on the target material consisting of a silicon crystal of dimensions 36 × 36 × 10 mm³, and all of the parts are maintained inside a copper holder. We explored the effect of two strategies to hold the target crystal, which are both presented in Fig. 1: the so-called “old” design based on PEEK clamps (left panel) and our “new” one (right panel) which uses bronze springs and sapphire balls to reduce the thermal contact and possible phonon losses.

In our first wifi-KID work [5], we used a pure 20 nm thick aluminium resonator, but the performance was not sufficient to distinguish the different calibration lines. In the present work, we report on the improvement in our detector response resulting from the use of multilayered Al/Ti materials. We fabricated two new types of resonators: Ti–Al (10–25 nm) and Al–Ti–Al (15–30–30 nm). Note that the ordering of the elements indicates the proximity to the Si target substrate such that for the Ti–Al devices the layer order is Si–Ti–Al (Fig. 2).

![Fig. 1 Schematic presentation of the two holders used in this study. The spacing between the resonator and the feedline is roughly 300μm. (Color figure online.) Left: 8 PEEK clamps are supporting the crystal target. Right: 4 PEEK clamps (with reduced dimensions) and 4 sapphire balls are supporting the crystal target](https://example.com/figure1.png)
In the following, we present the resulting tests and characterisations of our four devices:

- Al 20 nm (already presented in [5] with new analysis)
- Ti–Al 10–25 nm (new holder)
- Al–Ti–Al 15–30–30 nm (old holder)
- Al–Ti–Al 15–30–30 nm (new holder)

Adding a layer of Ti for the resonator induces a lower $T_c$ and thus a lower superconducting energy gap. To achieve low enough temperatures we used another cryostat for multilayered resonator than the pure Al sensor. The base temperature for this dilution cryostat, which was used for NIKA 1.5 development [7], is around 90 mK and does not benefit from vibration decoupling system like our low noise dry cryostat [6].

The two calibration sources used were a $^{241}$Am sample which produces alpha particles ($\sim$5 MeV), 60 keV gammas and low energy X-rays around 20 keV, and a $^{55}$Fe radioactive source producing $\sim$6 keV X-rays. Since the alpha particles are too energetic and lead to non-linear detector response we added a polyimide tape layer to stop them. In silicon, the interaction length of 60 keV gamma is about 1 cm which is comparable to the target thickness. The gammas will therefore deposit their energy uniformly in the target crystal. On the contrary, the emitted X-rays will interact only at the surface due to their short $\sim$ 30$\mu$m penetration depth.

2 Characterization, Calibration and Signal Processing

We developed a dedicated characterization and calibration procedure. The first step is an equilibrium characterization. This means that we study the characteristics of the resonator with respect to the thermal bath temperature of the cryostat. The idea is to evaluate the quality factors and the resonance frequency of the resonator at...
equilibrium for different temperature using a standard procedure [8]. As explained in [5], measuring the relative detuning allows us to estimate the kinetic inductance ratio $\alpha$ as well as the energy gap $\Delta$.

The measurements performed on all of our devices are shown in Fig. 3. Because the critical temperature is material dependent we choose to use the reduced temperature $T/T_c$ to fairly compare all four devices.

Our results suggest that the pure aluminum device is the most sensitive, as one could have expected from its lower thickness, and that we successfully achieved high quality factors, especially for the Al–Ti–Al device with $Q_i \approx 10^6$. Unfortunately, we found that the Ti–Al device did not work properly as it exhibited a very low overall quality factor and a degraded energy resolution compared to other devices. This device will therefore not be considered in the remainder of this work comparing the performance and response of our detector prototypes.

This equilibrium characterization allows us to gather a large amount of information concerning our devices. However, the behavior of resonators is slightly different for non-thermal excitation and thus the calibration requires a dedicated out-of-equilibrium study, which is the second step of our characterization phase. A common approach is to consider that the signal of one resonator is two dimensional, with a phase ($\theta$) and a radius ($r$) relative to the resonant circle at the base temperature [1].

The acquired signals are the In-phase component ($I$) and the Quadrature component ($Q$) of the feedline signal, obtained using dedicated timestream data acquisition setup as already discussed in [5]. In our setup, an impedance mismatch induces a shift in $I/Q$ plane (ie. the complex plane) when we switch from the VNA (Vector Network Analyzer) to timestream data acquisition setup. This imply that we cannot (directly) use the circle extracted from the frequency sweep to convert our $I/Q$ signal into a $\theta/r$ representation.

**Fig. 3** Left—Relative detuning versus reduced temperature for multiple devices. Right—Quality factors for the corresponding devices, from top to bottom: $Q_{\text{coupling}}$, $Q_{\text{total}}$, and $Q_{\text{internal}}$. (Color figure online)
We fitted this relaxation response in the complex plane with a circle discarding the non-linear part of its response (i.e., using the high-end of the pulse decay). This procedure is illustrated in Fig. 4 where the temporal data are shown in the left panel, their representation in the complex plane in the central panel, and the residuals as a function of the phase shift $\theta$ from the fit in the right panel. We applied this $I/Q$ to $\theta/r$ conversion procedure for each set of temperature and attenuation power at which the resonator was operated for our subsequent analyses.

In the region of interest, defined as $\leq 100$ keV energy deposition in the Si target, we derive an average phase sensitivity around $\sim 0.5$ mrad/keV. We can see this region highlighted in the inset of right panel of Fig. 4, suggesting also that the resonator response is dominated by the change of kinetic inductance, so mostly in the direction of the phase. The dynamic (linear) range for pure Al resonator extends up to the $\sim$MeV scale (equivalent to a phase shift of 1.5 rad). We performed different tests such as varying the readout power over a range of $\pm 20$ dB, and operated these detectors in three different cryogenic (and electronics) setups. In each case we observed similar resonator response with no pulse shape variations. The pulses lay precisely on the same calibration circle up to $\sim 100$ keV, suggesting that our detector response is linear up to this energy deposition in the absorber.

Measuring $\theta$ (derived from the $I$ and $Q$ signals) continuously over time and performing offline signal processing (including offline triggering) allowed us to extract characteristic pulse shapes for each bath temperatures. The data processing pipeline used to estimate the amplitude of the pulses is based on optimal filtering and was primarily developed for the Ricochet experiment [2].

3 Detector Dynamics and Performance

To gather information about the detector dynamics, we fitted the pulses observed at different bath temperatures. Our fitting model is motivated by the (at least) three expected time constants from the quasi-particle recombination rate, the resonator ring down time and the phonon lifetime inside the target. This phonon lifetime can

![Fig. 4 Left: ~MeV scale pulse in temporal space (4 ms time window). Center: Same pulse but in IQ plane with the VNA scan circle (f sweep) and calibration circle (from fit) superimposed. Ten seconds of data are represented in gray there. Right: Residuals of the fit with inset zoom of the region of interest. Blue: One ~MeV pulse used for $\theta/r$ calibration. Red: Considered part of the pulse used in the fit](image-url)
be set by the phonon down-conversion at surfaces and/or by the phonon absorption inside the resonator. The three exponential model is generally preferred but, for pure Al device, considering only two time constants appears to be sufficient. This suggests that, for pure Al device, two of the three processes have very close time responses or one of the three processes is negligible.

The result of these fits is shown on Fig. 5 and leads us towards multiple conclusions.

First, the change of holder (and thus thermal leak) does not seem to have an impact on the pulse shape (red and green in Fig. 5), suggesting that the thermal link to the cryostat does not drive the dynamics of our detector. Despite different ring down times for each holder configuration, we observed no significant differences in the pulse shape, suggesting that the ring down time does not affect the detector response.

All decay times ($\tau_1$, $\tau_2$) are almost constants with $T/T_C$, suggesting that a decay time determined by the quasi-particle recombination rate is disfavored. It is, however, worth highlighting that the one order of magnitude difference in the decay time constant $\tau_1$ between Al and Al–Ti–Al resonators could potentially be attributed to the differences in the superconducting gap. Indeed, the lower gap for Al–Ti–Al resonator does imply a larger fraction of phonons being able to break Cooper pairs later in the phonon down-conversion process, hence slowing down the pulse relaxation. Additionally, it is also worth noticing that the Al–Ti–Al resonator is 3.75 times thicker than the pure Al one (see Table 1). Future tests with a 75 nm pure Al resonator are planned to investigate the possible impact of the resonator thickness on the resonator decay time constant.

The rise time $\tau_3$ is the only characteristic time which features a $T$ dependence, and $\tau_3$ scales with the critical temperature $T_C$. For the pure Al resonator, this rise time is fully compatible with the ring down time, but the interpretation becomes more difficult when considering the Al–Ti–Al data. More measurements are planned to

![Fig. 5](image-url) Fitted characteristic times at different bath temperature compared as a function of the reduced temperature $T/T_C$. Green: Al–Ti–Al 15–30–30 nm in old holder. Red: Al–Ti–Al 15–30–30 nm in new holder. Yellow: Al 20 nm. Pentagon: Dominant decay time. Cross: Additional decay time. Diamond: Rise time. Solid lines Resonator ring down time, $\tau_{\text{ring}} = Q_{\text{total}}/(\pi f_0)$. Pulses from Al–Ti–Al data are shown at the bottom right for different bath temperature.
address this tension, such as applying the method from [4] to estimate $\tau_{qp}$ and alleviate the remaining degeneracies in our pulse shape interpretation.

As shown in Fig. 6, thanks to the use of Al/Ti/Al multilayers, we can properly recover both surface and bulk calibration lines from low-energy X-rays and 60 keV gammas, respectively. Figure 6 also shows the comparison between our observed energy spectrum (red) and the Geant4 simulations (black) smeared with our observed energy resolution with an additional energy dependent correction factor of 1.2% to correct for detector non-linearity at increasing energies. The excess of events on the right side of the 60 keV peak is attributed to pile-up events due to the high gamma emission rate of our calibration source.

4 Conclusion

The use of multilayered Al/Ti material improved the performance of the wifi-KID in terms of peak resolution. We are now able to identify the calibration peaks in the amplitude spectrum, which was not possible with the previous design in pure

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**Table 1** Summary of the various results obtained by the wifi-KID investigators

| Material    | Al     | Ti–Al | Al–Ti–Al |
|-------------|--------|-------|----------|
| Thick. (nm) | 20     | 10–25 | 15–30–30 |
| $T_c$ (K)   | 1.40   | 0.76  | 0.80     |
| $\Delta$ (µeV) | 213   | 115   | 123      |
| $\alpha$ (%)| 30     | 11    | 15.5     |
| $f_0$ (MHz) | 564.57 | 577.18| 589.36   |
| $\sigma$ (keV) | 2     | N.A.  | 1.5      |
aluminum [5]. With a reported 1.5 keV baseline resolution (RMS), these devices are still not sufficiently good to claim that our prototypes are competitive in the field of low-energy and rare event searches. But this work is a significant step towards the optimization of this cryogenic detector technology with proven and reliable multiplexing capability for future highly segmented large detector arrays.

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Data Availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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