Al/Ti/Al phonon-mediated KIDs for UV–vis light detection over large areas

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Abstract
The development of wide-area cryogenic light detectors with baseline energy resolution lower than 20 eV RMS is essential for next generation bolometric experiments searching for rare interactions. Indeed the simultaneous readout of the light and heat signals will enable background suppression through particle identification. Because of their excellent intrinsic energy resolution, as well as their well-established reproducibility, kinetic inductance detectors (KIDs) are good candidates for the development of next generation light detectors. The CALDER project is investigating the potential of phonon-mediated KIDs. The first phase of the project allowed to reach a baseline resolution of 80 eV using a single KID made of aluminum on a 2 × 2 cm² silicon substrate acting as photon absorber. In this paper we present a new prototype detector implementing a trilayer aluminum–titanium–aluminum KID. Taking advantage of superconducting proximity effect the baseline resolution improves down to 26 eV.

Keywords: kinetic inductance detectors, phonon-mediated light detectors, rare events searches, superconducting device

(Some figures may appear in colour only in the online journal)

1. Introduction
In the last decade, kinetic inductance detectors (KIDs) [1] underwent a rapid development, allowing their successful application to millimeter [2] and UV astronomy [3]. Different projects are currently on-going with the aim to apply this technology to other fields, ranging from the search of extrasolar planets [4] to x-ray spectroscopy [5, 6].

The CALDER project [7] is developing large area phonon-mediated KIDs with the aim of detecting small amounts of ultraviolet-visible (UV–vis) light. Such detectors will play a crucial role for the next generation bolometric experiments searching for neutrinoless double-β decay. CUORE [8], the current leading bolometric experiment, is an array of 988 TeO2 crystals read by NTD sensors. Its sensitivity to double-β decay is mainly limited by the background induced by the α radioactivity of the material surrounding the detector at cryogenic temperature, mainly copper. The possibility to distinguish different particles would allow to overcome this limit. Particle identification could be accomplished by measuring the Cherenkov light (≈100 eV) emitted in a TeO2 crystal by electrons, that are the signal candidates, but not by α particles [9–11]. CUPID [12, 13],

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the planned upgrade of CUORE, will therefore require light
detectors able to monitor the whole face of a crystal (~25 cm²)
with a baseline energy resolution good enough to clearly detect
this tiny amount of light (<20 eV RMS).

One of the limits of KIDs is that they can reach a max-
imum sensitive area of a few mm² [14]. To increase the
sensible area to several cm² we opted for a phonon-mediated approach [15]: photons are absorbed by the silicon substrate
on which the KID is deposited and produce athermal or
ballistic phonons able to reach the KID, where they break
Cooper pairs and generate a signal. The use of KIDs as
phonon-mediated detectors was proposed for the detection of
dark matter [16], cosmic rays [15] and x-rays [17, 18].

KIDs base their working principle on the kinetic inductance of
Cooper pairs, which can be modiﬁed by an energy release able
to break them into quasi-particles (QPs). If the superconductor is
inserted in a resonant RLC circuit with high quality factor
(Q > 10⁵), the density variation of QPs modiﬁes the transfer
function S(ω) of the resonator both in phase and in amplitude.
The phase readout is usually preferred since the phase response is
larger (up to a factor 10) and is given by [21]:
\[
\frac{d\phi}{dE} = \frac{\alpha S_0(\omega, T) Q}{N_0 V \Delta^0_b},
\]
where \( \eta \) is the energy to QPs conversion efﬁciency, \( \alpha \) is the
fraction of kinetic inductance with respect to total inductance, \( \Delta_0 \)
is the superconducting gap, \( N_0 \) is the single spin density of states
and \( V \) the detector volume. \( S_0(\omega, T) \) is a dimensionless factor
given by the Mattis–Bardeen theory, describing the phase
responsivity as a function of frequency and effective temperature
[22]. Finally \( Q \) is the quality factor of the resonator. The detector
described in [20], made of a 60 nm thick Al ﬁlm, featured \( \eta = 7.4\% \), \( \alpha = 2.5\% \), \( Q = 1.5 \times 10⁵ \), \( \Delta_0 = 179 \mu\text{eV} \), \( V = 2.4 \times 10^7 \mu\text{m}³ \), \( S_0 = 2.85 \), while for aluminum \( N_0 = 1.72 \times 10^{20} \text{eV}^{-1} \mu\text{m}^{-3} \).

One way to improve the responsivity is to increase the
fraction of kinetic inductance \( \alpha \) and to reduce the super-
conducting gap \( \Delta_0 \), without affecting signiﬁcantly the other
parameters in equation (1). This can be achieved by exploit-
ing the superconducting proximity effect between aluminum and a lower gap superconductor, such as titanium. Titanium
also features a higher kinetic inductance due to its higher
penetration depth [23] leading to a signiﬁcant increase of
\( \alpha/\Delta_0 \). However titanium was never demonstrated to work as

a high quality factor resonator, possibly because of its high
sensitivity to contaminants [24], yielding dissipative conduc-
ting states. This leads us naturally to protect titanium with
aluminum, which is known to have an almost lossless self-
protection oxide layer. Moreover, to efﬁciently collect pho-
nons from the substrate into the superconductor it is important
to have an acoustic impedance matching between the sub-
strate and the KID. In that respect, aluminum provides a better
coupling to silicon than titanium [25]. The geometry, we present,
is thus an Al–Ti–Al trilayer with the following thicknesses:
Al 14 nm/Ti 33 nm/Al 30 nm.

The fabrication of the chip was made according to the fol-
lowing steps. The intrinsic 380 µm thick Si (100) wafer is dipped
for 1 min in dilute 5% HF solution and then rinsed in deionized
water water for 1 min. The wafer is then moved to an electron
beam evaporator dedicated to superconducting materials, where
the layers are subsequently evaporated at rates of 0.5 nm s⁻¹ in
a residual vacuum of 4 × 10⁻¹⁰ mb. This is important especially for
titanium to avoid trapping impurities in the layer [24]. The film is
patterned using standard UV lithography followed by a two-step
wet etching. In a ﬁrst step, the aluminum is removed using a com-
mercial etchant (H₃PO₄/HNO₃/CH₃COOH). Then, in the
second step, the titanium and the bottom aluminum layers are
etched in dilute HF (0.05%) at a rate of about 0.2 nm s⁻¹.

The sensor implements a LEKID design [26] identical to the
Al detector in [20]. Its active area consists of an inductive
meander made of 30 connected strips of 62.5 µm × 2 mm. The meander is closed with a capacitor made of two
digitized ﬁngers of 1.2 mm × 50 µm. The silicon substrate is
diced into a 2 × 2 cm² detector with the KID in the center as
shown in ﬁgure 1. The chip is assembled in a copper structure
and held by 4 PTFE supports with total contact area of about
3 mm². The copper holder is thermally anchored to the mixing
chamber of a ³He/⁴He dilution refrigerator with base
temperature lower than 10 mK.

3. Electrical and thermal characterization of the
detector

The electrical characterization of the KID is based on the
study of the complex transmission \( S(ω) \) of the resonator

![Figure 1.](image)
around the resonant frequency (figure 2). The frequency dependence of the transmission of a resonator is ideally well described by a single-pole approximation. It is however necessary to take into account also impedance mismatches, power distortion and electronics nonlinearity to perform a rigorous estimation [27]. This measurement allows one to extract the coupling quality factor $Q_c$, the internal quality factor $Q_i$ and the total quality factor $Q = (Q_i^{-1} + Q_c^{-1})^{-1}$.

The resonant frequency is found to be close to 2.4 GHz. $Q_i$ is $1.48 \times 10^5$ in very good agreement with the value predicted by the SONNET electromagnetic simulation of about $1.5 \times 10^5$. $Q_c$ is estimated as $6 \times 10^3$, lower than our typical samples made of aluminum [20], but high enough to allow the detector to operate well.

The critical temperature and the resistance of the trilayer film have been measured in a 4-terminal geometry. The superconducting transition was measured at $(805 \pm 10)$ mK with a normal state resistance per square $R_{sq} = 0.58$ $\Omega$/sq above the transition. We estimate theoretically the $T_c$ of the trilayer following [28], assuming perfect interface transparency to phonons across the layers and a superconductor total thickness comparable or lower to its coherence length. Solving the Usadel equations [29] within these assumptions yields an analytical dependence of $T_c$ on the thickness of the layers, similar to that found in the Cooper model [30]. To apply straightforwardly this bilayer model to the Al/Ti/Al trilayer, we treat it as a bilayer Al–Ti taking the average thicknesses of the Al layers [31]. The expected critical temperature from this model is $T_c = 720$ mK, assuming values of $T_c$ for the single layers that take into account the increase of critical temperature in thin films, as described in [32]. The discrepancy between the expected $T_c$ and the measured value may come from the limitations of the model: we do not know the precise values of the electron–phonon coupling in all the layers, the actual transparency of the interfaces and also the actual $T_c$ for each layer. A more complete model was recently proposed in [33] and its experimental validation will be the subject of a separate work.

Using the SONNET electromagnetic simulations software we estimate the amount of kinetic inductance $L_k$ needed to shift the resonant frequency from the value simulated for a perfect conductor ($L_k = 0$) to the measured value. The simulation is calibrated against a detector with identical geometry but in aluminum. $L_k$ of the calibration device was calculated independently using direct measurements of $T_c$, $R_{sq}$, film thickness and an estimation of $\alpha$ from resonant frequency shift with temperature. We obtain a value of $1.4$ pH/sq, which is significantly higher than the value of $1.0$ pH/sq obtained using the BCS form described in [14], which depends on $T_c$ and $R_{sq}$. This is a first hint that our case of inhomogenous superconductor cannot be well described by the BCS theory. The obtained value of kinetic inductance translates into a kinetic inductance fraction $\alpha = 17\%$, much larger than that obtained in aluminum ($\alpha = 2.5\%$) using the same design [20].

We have also measured the relative variations of the resonant frequency $(f - f_0) / f_0$ as a function of temperature (figure 3). These data are compared with a model developed by Gao et al [34] using the Mattis–Bardeen theory. The model is calculated for our best estimation of the parameters ($T_c = 805$ mK and $\alpha = 17\%$). Again the BCS form
cannot describe properly the case of our inhomogeneous superconductor and we can indeed see the data departing from the BCS model at intermediate temperatures. The interpretation of these measurements needs a dedicated model, whose development is beyond the scope of this paper.

4. Detector performance

Our experimental setup allows to back-illuminate the detector using two different sources: a non-collimated x-ray $^{55}$Fe source and an optical fiber coupled to a fast room temperature LED. The $^{55}$Fe source illuminates in an almost uniform way the whole substrate with a rate of 1 Hz. The LED emits photons at 400 nm in the typical range of Cherenkov light. Depending on the LED pulse duration and/or amplitude, a variable number of photons can be sent onto the substrate. The whole optical system is initially calibrated with an accuracy of 10% using a PMT at room temperature and then cross-calibrated with the $^{55}$Fe source. The position and size of the optical system spot on the substrate is shown in figure 1.

The resonator is excited and probed with a monochromatic tone at the resonant frequency $f_0$. The output signal is fed into a CITLF3 SiGe cryogenic low noise amplifier, downconverted at room temperature using a superheterodyne electronics and then digitized with an acquisition card at a sampling frequency of 500 kSPS. Time traces of up to 12 ms of the real ($I$) and imaginary ($Q$) parts of $S_{21}$ are acquired following a software trigger. Finally $I$ and $Q$ variations are converted into changes of phase and amplitude relative to the center of the resonance loop. A detailed description of the experimental setup of our laboratory at INFN Rome, including the room temperature electronics and the acquisition software, can be found in [7, 35].

As already mentioned, the phase response is typically larger than the amplitude one. However the phase noise exhibits often an excess noise, which sometimes makes it advantageous to consider both phase and amplitude responses in the analysis of the detector sensitivity. When amplitude and phase noises are dominated by the noise of the low noise amplifier, they decrease with microwave power as $S_N \propto P_{in}^{-1/2}$; however at large powers the nonlinearities of the kinetic inductance [36] and heating effects [37] become relevant and can suppress the signal. The recombination time...
For this purpose, we perform a microwave power scan in figure 4 right we show the signal-to-noise ratio, obtained with the Al detector in figure 7 right assuming that two uncorrelated components contribute to the detector resolution: the baseline resolution \( \sigma_B \) and the Poissonian term from the photon counting that we model as10 \( \sqrt{\bar{m} \times \tau} \), where \( \tau \) is the responsivity per photon which is estimated from the fit: \( \sigma = \sqrt{\sigma_B^2 + m \times r} \).

The trailing edge of the pulse is well described by a single exponential law with a decay time that varies between 800 and 100 \( \mu \)s with increasing microwave power (figure 5). As shown in [38], this decay constant can be interpreted as \( \tau_{QP} \). The noise power spectrum at optimal power is reported in figure 6 for both the phase and amplitude readouts. The flat noise observed in the amplitude readout and in the high frequency region of the phase readout, is consistent with the noise temperature of the cold amplifier \( T_0 \sim 6 \text{ K} \). This noise is exceeded by a low-frequency phase noise, whose spectral index is found to be 0.49 \( \pm 0.05 \), consistent with the presence of a two-level system noise in the detector, observed often in KIDs [40]. In order to compare the obtained TLS noise with other works, we convert the noise in fractional frequency noise as in [14] and get \( S_{TLS}(f = 1 \text{ KHz}) = 1 \times 10^{-21} \text{ Hz}^{-1} \), that is among the best values reported in [14]. Both power spectra show also peaks due to the readout electronics. These peaks are strongly suppressed by the matched filter and the measured energy resolution is always found consistent with the predictions from the noise power spectrum and the matched filter.

To obtain a solid estimation of the detector performance we implement a calibration based on the Poisson statistics of the photons absorbed into the substrate. The detector is biased at the optimal microwave power of \(-70 \text{ dBm} \) and is illuminated with optical pulses of energies in the range 0–3 keV. For each energy the distribution of the pulse heights in the phase readout is found to be well described by a Gaussian with mean \( \mu \) and standard deviation \( \sigma \) (figure 7 left). The \( \sigma \) versus \( m \) data are then fitted (figure 7 right) assuming that two uncorrelated components contribute to the detector resolution: the baseline resolution \( \sigma_B \) and the Poissonian term from the photon counting that we model as10 \( \sqrt{\bar{m} \times \tau} \), where \( r \) is the responsivity per photon which is estimated from the fit: \( \sigma = \sqrt{\sigma_B^2 + m \times r} \). By dividing \( r \) by the energy of a single photon counted with the Al detector in figure 4 left. The phase response is quite flat with increasing power around 19 mrad keV\(^{-1}\), a sizeable improvement with respect to the 6 mrad keV\(^{-1}\) obtained with the Al detector in [20]. A similar increase is observed for the amplitude response, around 2.5 mrad keV\(^{-1}\) with respect to the 0.6 mrad keV\(^{-1}\) obtained with the Al detector.

In figure 4 right we show the signal-to-noise ratio, obtained by dividing the amplitude of the pulses by the RMS of their baseline (after the matched filter). We determine an optimal working power of \(-70 \text{ dBm} \), about 10 dB lower than what obtained with aluminum. The efficiency \( \eta \) at the optimal working power is estimated as in [20] and amounts to \( \eta = (7.5 \pm 1)\% \) consistent with what found in [20].

The number of photons absorbed in the detector is \( N_{ph} = m/r \). According to the Poisson statistics one has \( \sigma_{ph} = \sqrt{N_{ph} \times r} = \sqrt{m/r \times r} = \sqrt{m \times \tau} \).
400 nm photon we obtain a responsivity of \((17.54 \pm 0.58 \text{ mrad keV}^{-1})\) in good agreement with the calibration against \(^{55}\text{Fe}\) presented previously in this section. Using this energy calibration we find a phase readout baseline resolution \(\sigma_f = (25.64 \pm 0.85) \text{ eV}\). Applying the same procedure to the amplitude readout, we obtain \(\sigma_A = (77.3 \pm 2.5) \text{ eV}\).

5. Conclusions and discussions

In this paper we presented the results obtained using an Al/Ti/Al trilayer film to develop a phonon-mediated KID for the detection of UV–vis light on large surfaces. The sample features \(T_c = 805 \text{ mK}, Q = 600 \text{ k}\) and a low-power recombination time \(\tau_{\text{OP}} = 800 \mu\text{s}\). The main features of the detector are compared in Table 1 with the Al detector, presented in [20]. The lower critical temperature increases significantly the fraction of kinetic inductance \(\alpha\) and thus the responsivity of the detector (factor 3 in the phase readout). The integrated phase noise after the matched filter improves of about 25%. This improvement can be ascribed likely to the change in the fabrication process: the new trilayer detector was made by etching while the previous detectors were made by lift-off. The overall result is the improvement of the RMS baseline resolution for phase readout from 105 eV down to 26 eV. The amplitude responsivity also improves (factor 4). Since the amplitude noise is dominated by the LNA noise, the lower bias power implies however a worsening of the integrated noise by a factor 3. Therefore the amplitude baseline resolution improves only from 115 to 77 eV. The obtained energy baseline resolution approaches the target resolution of the CALDER project of 20 eV. The last phase of the project—currently in progress—consists in the development of light detectors of \(5 \times 5 \text{ cm}^2\).

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