Niobium-Based Kinetic Inductance Detectors for High-Energy Applications

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SUMMARY A lumped element kinetic inductance detector (LeKID) relying on a superconducting resonator is a promising candidate for sensing high energy particles such as neutrinos, X-rays, gamma-rays, alpha particles, and the particles found in the dark matter owing to its large-format capability and high sensitivity. To develop a high energy camera, we formulated design rules based on the experimental results from niobium (Nb)-based LeKIDs at 1 K irradiated with alpha-particles of 5.49 MeV. We defined the design rules using the electromagnetic simulations for minimizing the crosstalk. The neighboring pixels were fixed at 150 μm with a frequency separation of 250 MHz from each other to reduce the crosstalk signal as low as the amplifier-limited noise level. We examined the characteristics of the Nb-based resonators, where the signal decay time was controlled in the range of 0.5–50 μs by changing the designed quality factor of the detectors. The amplifier noise was observed to restrict the performance of our device, as expected. We improved the energy resolution by reducing the filling factor of inductor lines. The best energy resolution of 26 for the alpha particle of 5.49 MeV was observed in our device.

key words: lumped element kinetic inductance detectors, superconducting sensors, high energy applications

1. Introduction

Superconducting detectors have attracted much attention in the field of high energy particle physics for detecting rare phenomena such as weakly interacting massive particle (WIMP) interactions in dark matter [1], [2], neutrinos [3], [4], and double beta-decay [5]. A low dark count, high sensitivity, large active area, and high operation temperatures similar to the lumped element kinetic inductance detector (LeKID) [6] are highly desired in the superconducting sensors including the transition edge sensors [7], superconducting nanowire single photon detectors [8], and superconducting tunnel junctions [9]. LeKID is a cousin of the kinetic inductance detector invented by the Caltech group [10], which consists of a superconducting resonator. Its resonance characteristics are determined by a lumped element circuit divided into inductors (L) and capacitors (C). When an incident photon energy breaks the Cooper pairs in the superconducting inductors, kinetic inductance originating from superconducting current changes, which causes a decrease in the resonant frequency $f_0 \propto 1/\sqrt{LC}$.

Here, we often design the detectors with resonant frequencies in the range of 3–8 GHz, because commercial or semi-commercial readout components are readily available to develop a readout chain in this frequency range. The readout chain consists of many circuits, such as cold low noise amplifiers (CLNA), signal generators, low loss cables, high-bit analog-digital converters, and even multiplex readout board [11], [12]. The noise temperature of the CLNA is critical for the performance of the LeKID, as the amplifier performance dominates the readout noise and energy resolution as follows,

$$\sigma_E = \frac{2\Delta^2 N_0 V_Q}{\eta_{qp} \alpha Q_L^2} \sqrt{\frac{k_b T_n}{P_{in} \tau_{qp}}}.$$  

Here, $\Delta$ is the superconducting gap energy, $N_0$ is the single spin density at the Fermi level, $V$ is the volume of the inductor, $Q_L$ is the loaded quality factor, $Q_c$ is the coupling quality factor between the resonator and the bias feed line, $\eta_{qp}$ ($\approx 0.57$) is the efficiency with which the energy is converted into quasiparticle excitation [13], $\alpha$ is the kinetic fraction [14], $k_b$ is the Boltzmann constant, $T_n$ is the noise temperature of a cold low noise amplifier, $P_{in}$ is the input bias power, and $\tau_{qp}$ is the quasiparticle recombination time.

Consecutive resonator arrays often have mutual coupling, which contaminated the signal of the neighboring resonators. Such crosstalk between resonators can be detrimental to the energy and spatial resolution of our device; however, the effects of crosstalk is not included in Eq. (1). When the resonant frequency of one resonator shifts due to the absorption of energy, it can also change mutual inductance and mutual capacitance of the device. As a result, the resonant frequencies of neighboring resonators move without receiving energy. Hence, it is important to reduce the effects of signal contamination below the amplifier noise levels. In this study, we estimate the crosstalk between two resonators using an electromagnetic simulation software and formulate the design guideline for the separation of physical and resonant frequency, as described in Sect. 3.

The LeKIDs have a relatively large detectable area, such as $(1 \times 1 \text{mm}^2)$, despite the smaller area of the inductors (the width of 3 μm and the length of 5 mm). The large stretch of the active area is owing to the phonon mediation via a substrate; however, the phonon-mediated signal may show a position dependence and degrade the energy resolution as discussed in [15]. Additionally, we detected that most of alpha particles hit between the inductors because the distance of the neighboring inductors was designed to be 100 μm,
since the phonon can traverse more than millimeters [15].

2. Basic Performance of Nb-Based Detectors

In this section, we describe the fabrication process, the measurement setup, the methods to analyze pulse responses, and controllability of the pulse relaxation time for evaluating the performance of our detector against alpha-rays.

2.1 Fabrications and Setups

We used niobium films sputtered on a 200-μm thick high-resistivity silicon that was used as the substrate and immersed in the HF solution to remove the natural oxide layer. The Nb-film thickness was 100 nm, and the device patterns were fabricated using the standard photolithography process and dry etching with CF$_4$ gas. The widths of the inductors and capacitors was selected as 3 μm. The critical temperature was observed to be 8.5 K. The resonant frequencies were designed to be in the range of 3.5–4.5 GHz. A chip has eight resonators, and each resonator has approximately $1 \times 1 \text{mm}^2$ active area, as shown in Fig. 1. For Nb-based detector, we calculated the value $\sigma_E \sim 470 \text{ eV}$ using Eq. (1); where the values of $\Delta = 1.1 \text{ meV}$, $N_0 = 1 	imes 10^{10} \text{ eV}^{-1} \mu\text{m}^{-3}$, $V = 3 \times 5700 \times 0.1 \text{ in } \mu\text{m}$, $Q_r \sim Q_C \sim 10^4$ in the $Q_C$ limit condition, $P_{in} = -60 \text{ dBm}$, $T_n = 7 \text{ K}$, $\tau_{qp} \sim 10^{-9} \text{ s at 1K}$, and $\alpha = 0.085$ were used.

Our measurement setup included a helium-3 circulation system installed on a 4-K Gifford-McMahon cooler. The cold stage of the cryostat was maintained below 1 K for a relatively longer time (more than a week). Owing to the short penetration depth of alpha-ray particles of 5.49 MeV—which is approximately 20 μm for silicon—the radioactive source (Americium 241 (Am-241)) was set inside the cryostat (Fig. 1). We glued a chip to a copper-based sample holder with the varnish (GE7031) and connected the feed line to the coaxial cable on the device by aluminum wire bondings. We use the standard readout chain with a microwave signal generator (Keysight N5173B), a cold low noise amplifier (Caltech Cryogenic LNA), an IQ mixer (Marki microwave IQ0307LP), and a digitizer (National Instruments PXI-5922) to measure complex transmission losses. We exhibit a resonant IQ circle (Fig. 2 (a)) and a resonant spectrum of the S21 (Fig. 2 (b)) as a function of frequency.

2.2 Pulse Analysis

The standard homodyne measurements were performed to obtain the time-domain streams of both I and Q signals as voltages. We set a threshold of five $\sigma$ values as the standard deviation and extracted the pulse signal from the entire stream. The alpha particles, irradiated from the source, enter the detector from the device side. The alpha-rays are absorbed by both the superconducting films and substrates. The energy absorbed by the superconducting films from the alpha ray photons directly excites the Cooper pairs, generating a pulse with higher amplitude. The events from the substrate originated due to the phonon-mediated signals. We set the threshold five times greater than the standard deviation of the amplitude ($\sigma$) to identify alpha-ray events, as shown in Fig. 2 (c). The signal to noise ratio of the direct event estimated to be approximately 60.

We can convert the pulse height to the number of quasiparticles excited in the inductors by using the temperature

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Fig. 1 Measurement equipment: a 4-K Gifford McMahon cryostat combined with the helium-3 circulation system maintains the cold stage below 1 K. The chip housed in a copper holder is installed on the stage, and the alpha source is placed in the 4 K shield. The complex scattering matrices of the sample were measured using the standard homodyne readout. The chip has 8 resonators, of which area is approximately $1 \times 1 \text{ mm}^2$.

Fig. 2 (a) Resonant circle as a function of frequency in the IQ plane (blue) and time response caused by an alpha particle at a fixed frequency (orange). (b) Resonant spectrum of a niobium-based resonator. (c) Pulse generated by the direct absorption events of niobium film and the inset shows the pulse height as a function of the number of quasiparticles in the resonator. Dashed line shows the threshold defined as 5 times greater than standard deviation ($\sigma$) of the signals.
dependent resonance behavior. The most significant signal obtained using our device yielded the number of excited quasiparticles as $0.6 \times 10^7$. Our results show the compression of the responsivities; however, no-saturation of the resonance signal was observed (inset of Fig. 2).

The decay time of the pulse in the range of 0.5–50 μs by changing the designed quality factor (Fig. 3). The decay time is determined by the combination of the resonance ringing time ($\tau_r$), the quasiparticle lifetime, and the phonon diffusion time. Since the resonators were located on the identical chip, we assume that the deviation of the physical relaxation time such as the quasiparticle lifetime and the phonon diffusion time were negligible between each pixel. The $\tau_r$ of a resonator is defined as $Q_i$, where $f_0$ is the resonant frequency. When $Q_i$ is 10000 and $f_0$ is 3 GHz, the ringing time should be approximately 1 μs. We changed the coupling quality factors ($Q_c$) ranging from 2 × $10^6$ to $2 \times 10^5.5$, and the internal quality factor ($Q_i$) was measured to be at most $7 \times 10^5$. The relationship between these quality factors is given by $Q_l = (1/Q_i + 1/Q_c)^{-1}$. As a result, the loaded quality factors differed from $8 \times 10^3$ to $6 \times 10^5$. Although the value of $\tau_{qp}$ for a Nb-film deposited on a silicon wafer is of the order of 1 ns [16], and is much shorter than $\tau_r$, the pulse response of the resonator to the alpha-ray particles was observed to be proportional to $(Q_l/f_0)^{1.05}$ (Fig. 3), which is consistent with the theory.

3. Crosstalk Simulations

To maintain the high spatial and energy resolution of the large-sized detectors, it is important to minimize the crosstalk between each pixel such that it is as low as the noise signal from the detector. For our device, the crosstalk level should be less than 1%, as the signal noise to ratio was around 60 with the alpha-ray sources described in Sects. 2 and 4.

The two major reasons for the crosstalk between pixels are the electromagnetic coupling between the resonators and the energy leakage through the substrate wafer. In this paper, we discuss the details for reducing crosstalk due to the electromagnetic coupling only; however, the energy leakage of the phonons can be prevented by creating physical gap between each pixel.

Noroozian et al. pointed out the difficulty in direct measurement of crosstalk between resonators in illuminated MKID. Thus, they evaluated the crosstalk in different manner, with ratio of resonance-frequency shift of resonators with off-resonant modes to that with on-resonant one when a frequency tone corresponding to the latter with large power enough for activating the current-dependent kinetic inductance is added to the microwave feedline of the MKID. In this evaluation, parameters of electromagnetic coupling between resonators are extracted by an electromagnetic (EM) simulator (Sonnet). We follow this approach and make basically similar EM simulation, but the following three points are our original. First, we chose the standard meander type inductors because the spiral inductors adopted in [18] were observed to have non-uniform current density with the EM simulator. Next, both inductive and capacitive couplings are taken into account in our work though only capacitive one is in [18]. Finally, spatial separation required in the actual operations of a high-energy camera with LeKID is first discussed.

To demonstrate the effect of mutual coupling between the resonators using a simple model, we used two identical resonators, and the equivalent circuit is shown in Fig. 4. In this model, the resonator consists of the inductor ($L$) and capacitor ($C$), and two resonance modes (even and odd modes) are observed. The even mode occurs at $V_1 = V_2$, and the odd mode is excited when $V_1 = -V_2$. The resonant frequencies of both the modes ($f_e$, $f_o$) can be calculated using Eqs. (2) and (3) [18].

![Fig. 3](image1.jpg) **Fig. 3** (top) Normalized responses of the high-Q resonator (dashed line) and the low-Q resonator (solid line), and the inset shows the transmission loss spectra of both the resonators. (bottom) Relationship between the pulse decay time $\tau$ and the quality factor of the resonator ($Q_l$) divided by the resonant frequency ($f_0$): $\tau \propto (Q_l/f_0)^{1.05}$.

![Fig. 4](image2.jpg) **Fig. 4** Equivalent circuit of electromagnetic coupling between two identical resonators, that gives Eqs. (2) and (3). Note that neither the microwave feedline nor the feedline-resonator couplings are shown in this figure. $L_m$ and $C_m$ indicates mutual capacitance and mutual inductance, respectively.
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\begin{align*}
    f_e &= \frac{1}{2\pi \sqrt{(L + L_m)(C - C_m)}} \quad \text{(2)} \\
    f_o &= \frac{1}{2\pi \sqrt{(L - L_m)(C + C_m)}} . \quad \text{(3)}
\end{align*}
\]

For the real device, we cannot use identical resonators, therefore we prepared two different resonators, namely resonator 1 and 2 with the base resonant frequency of \( f_1 = \frac{1}{2\pi \sqrt{L_1/C_1}} \) and \( f_2 = \frac{1}{2\pi \sqrt{L_2/C_2}} \), respectively. Although these equations for the base resonant frequencies do not involve the effect of crosstalk between the two resonators, we have used these equations for simplicity, as the complex equations of \( f_e \) and \( f_o \) needed in such a case are beyond the scope of this paper. Nonetheless, we were able to distinguish the even and odd mode by analyzing the current density in the ground plane between the two resonators using the EM simulator. We assigned \( f_o = f_1' \) and \( f_e = f_2' \) because \( L_m/L < C_m/C \) indicating \( f_o < f_e \) in our device arrangement.

To minimize the effect of crosstalk, we changed the distance between the two resonators with resonant frequencies, \( f_1 = 3.073 \text{ GHz} \) and \( f_2 = 3.079 \text{ GHz} \) without mutual coupling. Here, we defined the distance as the length from the rightmost inductor of the left pixel to the leftmost inductor of the right pixel. We calculated the resonant frequency including the effect of the crosstalk \( (f_1' \text{ and } f_2') \) using the EM simulator and we derived the frequency shifts of each pixel \( (f_1' - f_1 \text{ and } f_2' - f_2) \). Note that the frequency shift in the vertical axis of Figs. 5, 6, 7 indicates how large the electromagnetic coupling is. The lower resonant frequency \( (f_1) \) decreased, and the higher resonant frequency \( (f_2) \) increased.

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**Fig. 5**  (top) Schematic of the space separation between two pixels for the crosstalk simulations. The shape of each resonator is fixed and the distance between two pixels is changed in range of 50–250 \( \mu \text{m} \). (bottom) Resonant frequency shift with changing in distance. Circles represent the data from the right resonator with the lower resonant frequency \( f_1 \) (in the top panel) and triangles indicate the left one with the higher resonant frequency \( f_2 \).

**Fig. 6**  (top) Schematic showing the frequency separation between two resonators for crosstalk simulations. The distance between each resonator is fixed at 20 \( \mu \text{m} \), and the geometry of the right resonator is fixed as well. We simulated it by changing the resonant frequency of the left pixel \( (f_2) \) in the range of 3.079–3.346 GHz. (bottom) Resonant frequency shift \( (f_1' - f_1) \) of the left resonator as a function of the resonant frequency separation between the two resonators.

**Fig. 7**  (top) Schematic showing the geometry of the resonators for the crosstalk simulations. The shape of both the resonators and the distance between them were kept, while the sheet inductance of the film in the right resonator varied from 0 (perfect conductor) to 0.1 pH/sq. The increase in the sheet inductance caused an decrease in the base resonant frequency of the right resonator. (bottom) Resonant frequency shift \( (f_2' - f_2) \) of the left resonator as a function of additional sheet inductance of the right resonator.
with a decrease in the distance, as shown in Fig. 5. The antisymmetric shift between the two resonators may be associated with the spatial dependence of the mutual inductance and the mutual capacitance.

Then, we simulated the value of $f'_k$ by modifying $f_2$ values ranging from 3.079–3.317 GHz at a fixed distance of 60 μm. $f'_k$ approached to $f_1$, as the frequency separation $(f_2 - f_1)$ increase (Fig. 6). The dependence of frequency shift on the frequency separation was fitted with the approximate logarithmic expression as shown below:

$$\Delta f = f'_k - f_1 = 6.92 \ln(f_2 - f_1) - 40.6.$$  \hspace{1cm} (4)

We could not conclude quantitative strength of crosstalk between the pixels from these simulations due to the lack of quantitative relation between “crosstalk” and “shift of resonance frequency”, but the calculations helped us to understand qualitative relation. Note that the important point of this part is that the variation of resonance frequency can be small by increasing $|f_2 - f_1|$, though we fixed $f_1 = f_2$ in the analytical model in Fig. 4.

Equations (2) and (3) indicate that a resonance frequency of $k$-th pixel without electromagnetic coupling $f_k$, where $k = 1, 2, \ldots$, is the pixel number, splits into two frequencies $f_{ke}$ and $f_{ko}$ due to nonzero $C_m$ and/or $L_m$, where $e$ and $o$ denote even (higher frequency) and odd (lower frequency) modes, respectively. In addition, $|f_{ke} - f_{ko}|$ becomes larger when $C_m/C$ and/or $L_m/L$ increase. For enough large $C_m/C$ and/or $L_m/L$, in the frequency domain, resonance frequency associated with the “odd” mode of a pixel $k$ with incoming photon. $f_{2o,e,w}$, can be close to that to the “even” mode of adjacent resonator in lower frequency order without incoming photon, $f_{(k-1)e,w}$. This makes difficulty both in the identification of pixels under the incoming photon and in the quantitative measurement of the energy of an incident photon. A criterion for avoiding this difficulty would be

$$f_{ko,w,p}(Max, energy) - f_{(k-1)e,w} \gg |f_{ke,w} - f_{ko,w}|.$$  \hspace{1cm} (5)

where $f_{ko,w,p}(Max, energy)$ denotes the resonance frequency of odd mode when the photon with the maximum energy under consideration comes into the $k$-th pixel. If one got the experimental or calculated values of $f_{ko,w,p}(Max, energy)$, one can propose other criteria of interpixel distance (Fig. 6), $f_{k+1} - f_k$ (Fig. 6), and surface inductance (Fig. 7), and we will consider them in the future.

4. Energy Resolution

In this section, we discuss the restrictions posed by the noise of the CLNA, differences in the origin of events (direct or phonon-mediated), and the filling factor of the inductor used in the resonator on the energy resolution of the Nb-based LeKID.

4.1 Dependence of Incident Direction

We calculated the energy depositions of the alpha-ray entering from the top and the bottom of the device. The total energy of the alpha-ray entering from the bottom of the device is completely absorbed by the silicon substrate because the penetration depth for the silicon substrate is approximately 20 μm, and the wafer thickness is 200 μm. However, we estimated the linear stopping power—defined as the power absorbed per unit depth—using Bethe theory for the alpha-rays entering the device from the top because the thickness of the superconducting film is only 100 nm. Since, there is no report on the stopping power of niobium in the literature, we estimated the stopping power of niobium films to be $-dE/dx \sim 300$ keV/μm by correcting the data for silver [17] considering the difference in the atomic numbers. The product of the stopping power and the film thickness yielded a value of the absorption energy as 30 keV.

The results of the alpha-rays entering the top and the bottom of the detector device using the identical resonators with a resonant frequency of 4.888 GHz were analyzed. As shown in Fig. 8, the spectra obtained with the top irradiations showed two distinct peaks: a sharp and high intensity peak due to the direct absorption by the superconducting Nb-film, and another peak in the lower energy range can be attributed to the phonon-mediated event due to the absorption of energy by the substrate wafer. When the alpha-rays entered the device from the bottom side, the spectra only showed the lower energy peak originating due to the phonon-mediated signal (Fig. 8).

We calculated the x-axis of the energy histogram using the relationship between the number of quasiparticles and the maximum height of the pulse (Fig. 2). The energy that excited the quasiparticles was found to be the product of $7.5 \times 10^6$ and $\Delta E_{Nb} = 1.1$ meV. We fitted the direct event peak with the Gaussian function and obtained a full width at half maximum of 17. This corresponded to an energy resolution

![Fig. 8 Observed spectra from the alpha-ray source, americium 241.](image-url)
of 1.8 keV, which is relatively larger than the expectation of \( \sim 470 \text{ eV} \) (given in Sect. 2.1).

The decay time should be mainly dominated by the resonator ringing time, as discussed above. However, we have slight differences between the top and bottom illumination. The signal decay time was derived with exponential fits started from the peak of the signal. However, the top and bottom illuminations yielded different signal decay times of 1.1 \( \mu \text{s} \) and 0.76 \( \mu \text{s} \), respectively, as shown in the inset of Fig. 8. The difference of the energy absorption process might bring this discrepancy, but we need more study to interpret them.

### 4.2 Effect of Amplifier Noise

The base energy resolution \( \sigma_E \) can be obtained using Eq. (1), where \( \sigma_E \propto \sqrt{S} \), because \( S \) is the noise power spectral density (PSD) and \( S = k_B T_s Z_0 \), where \( Z_0 \) is the impedance of the readout coaxial cables. To distinguish the effects of the noise temperature differences of the CLNA, we compared the performance of two resonators on the same chip. We irradiated the alpha particles from the top side of the device and measured the noise PSD and alpha-ray events at 1K. As shown in Fig. 9, the energy resolution of LeKID directly depends on the PSD. The LeKID with the resonant frequency of 4.888 GHz had the PSD of \(-96\ \text{ dBc}\), and the resolution of 17 and the pixel of the resonant frequency of 4.611 GHz has the PSD of \(-100.5\ \text{ dBc}\) and the resolution of 26. The noise fluctuation of 4.5 dB corresponded to increment by the factor of 1.67 and the discrepancy of the observed resolution was \( \frac{26}{17} = 1.53 \). To improve the resolution further, a lower noise amplifier such as a parametric amplifier [19] as the first amplifier of the readout chain may be used.

### 4.3 Substrate Event Reduction

The energy resolution of LeKID for the detection of high energy particles also depends on the square root of an active area [15]. The effect of an active-area with the high-filling factor pixel (Fig. 10(a)) and the low-filling factor LeKID (Fig. 10(b)), on the detection rate is shown. In this experiment, the filling factor and length of the inductors was changed without changing the separation between the inductors. When the alpha-rays entered from the top side, two different types of events, including the direct absorption in the superconducting film and the phonon-mediated signal due to the absorption by the Si substrate, occurred. The direct event rate of the device observed in case of low filling rate (b) is expected to be smaller than that of the high filling rate of the device (a); however, the absolute event rates could not be compared because these rates can easily change depending on the positional relationship between the chip and the alpha-source. Therefore, we verified the ratio of the indirect event to the direct event for both the cases, and the ratios of 0.3 and 0.07 were obtained for the high-filling factor and the low-filling factor devices, respectively.

The energy resolution calculated using the event ratio...
of the direct and indirect signal shows that the device (b) with low filling factor has a better energy resolution, which is \sqrt[0.7]{0.3/0.07} \approx 2 times better than that of the device (a) with high filling factor. The energy resolution of the devices (a) and (b) were estimated as 14 and 26, respectively, by using the Gaussian fits of the direct-event peaks. Our experimental results are consistent with the theory, confirming that the smaller active area device shows a better energy resolution but the worst detection efficiency.

5. Conclusion

Nb-based LeKIDs are a good candidate for the high energy particle sensors with large-format, high-sensitivity, and high-speed capabilities. In this study, we fabricated 8-pixel arrays on a 10 mm square chip that can be easily expanded up to a few hundred pixel using a massive chip with large number of sensors. The relaxation time of the signals can be controlled by changing the detector design and the best sampling rate of 300 kHz was observed. The energy resolution was observed to be strongly dependent on the amplifier noise as well as the effects of the phonon-mediated event through the substrate wafer. The best resolution of 1.2 keV at 30 keV was obtained, which is 2.5 times greater than the expected value.

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References


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