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Characterization of Lumped Element Kinetic Inductance Detectors on YSZ Substrates for ^{94}Zr Double-Beta Decay Search

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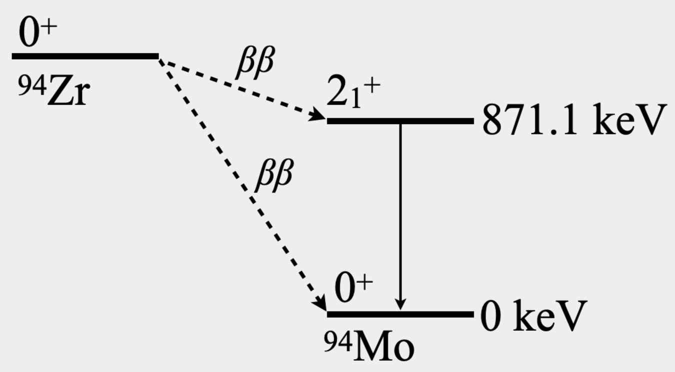
Double-beta decay is extremely rare radioactive decay in which two neutrons are simultaneously into two protons with two electron emission. It has two mode: two neutrino emission mode ($2\nu\beta\beta$) and undiscovered neutrinoless mode ($0\nu\beta\beta$). The key of $0\nu\beta\beta$ detection is high energy resolution of detectors. A lumped-element kinetic inductance detector (LEKID) is a thin-film superconducting resonator with larger sensitive volume. Radiation detection using LEKID is expected to have high energy resolution due to its detection principle. Here, we proposed the ^{94}Zr double-beta decay search with LEKID. Yttria-Stabilized Zirconia (YSZ) was utilized for LEKID substrate. This is the first step in realizing the implementation of LEKID on the substrate including zirconium for ^{94}Zr double-beta decay search.

1. Double-Beta Decay of ^{94}Zr

Even $2\nu\beta\beta$ of ^{94}Zr has not been yet discovered.

- **Decay mode**
  $^{94}\mathrm{Zr} \longrightarrow {}^{94}\mathrm{Mo} + 2e^- + 2\overline{\nu}_e$
  Q-value : 1.1 MeV
  To Excited State $0^+ \rightarrow 2_1^+$:
  Q-value 0.23 MeV $\beta\beta$
  +
  0.87 MeV deexcited γ



- **$2\nu\beta\beta$ half-life prediction and current limits:**

Decay mode of $2\nu\beta\beta$	predicted [yr] [1]	limit [yr]
$0^+ \rightarrow 0^+$	9.4×10^{21}	1.1×10^{17} [2]
$0^+ \rightarrow 2_1^+$	7.2×10^{32}	2.1×10^{20} [3]

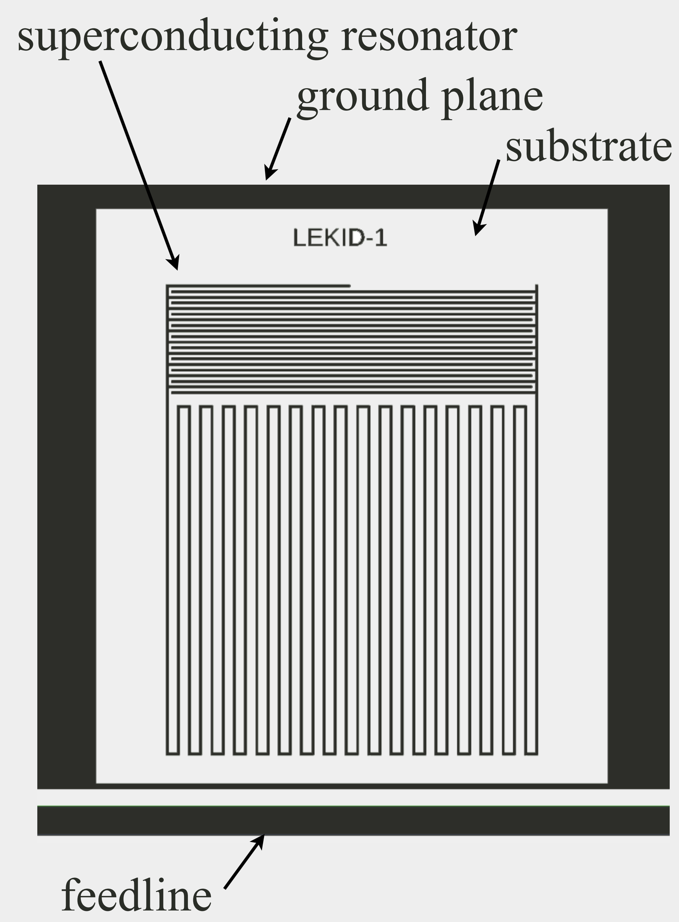
- **Previous study**
  NEMO-2 : Mainly search for ^{96}Zr $0\nu\beta\beta$ in underground
  $\longrightarrow$ Limit on ^{94}Zr $2\nu\beta\beta$ is byproduct [2].
  HPGe detector experiments : High sensitivity to $0^+ \rightarrow 2_1^+(\gamma)$ [3]
- **Key of improvement**
  High efficiency $\longrightarrow$ "source" = "detector"
  High S/N $\longrightarrow$ High energy resolution

2. LEKID [4]

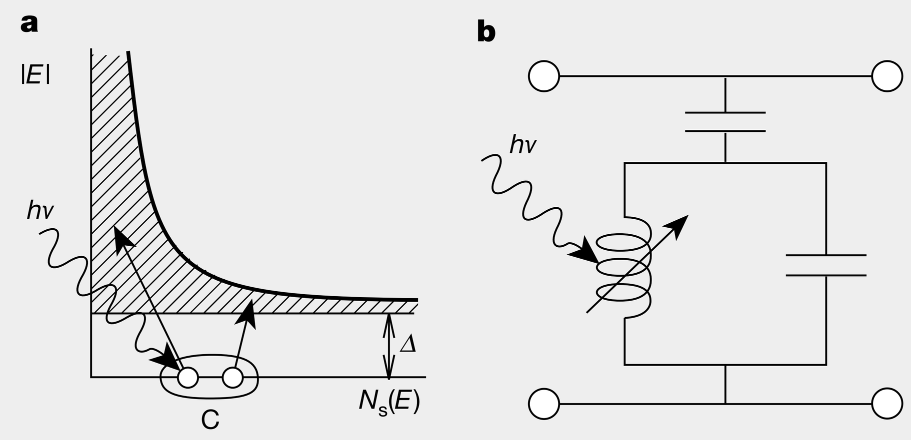
- Superconducting resonator with large sensitive volume
- Multi-elements readout possible with a single feedline
- Low energy threshold, and High energy resolution potential

[Detection Principle]
Energy input[a] → Cooper pair breaking[a]
→ Kinetic inductance change[b] → Resonant frequency change

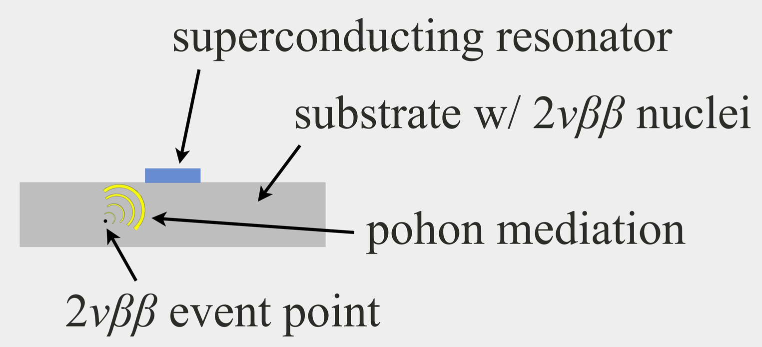
Detect!



Design of LEKID



Detection principle *excerpted from* [5]

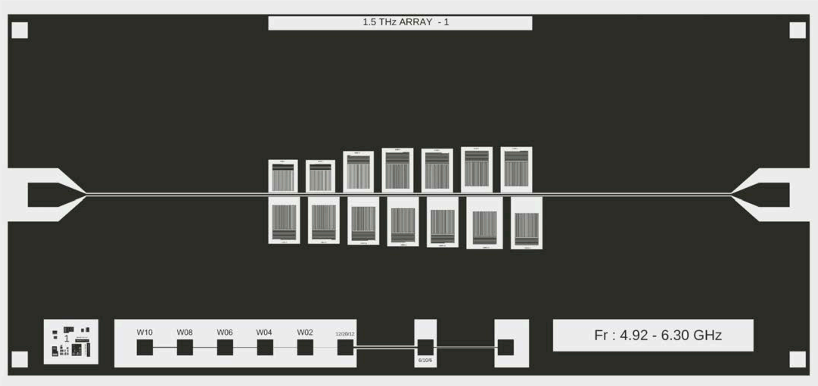


Concept for $2\nu\beta\beta$ detection

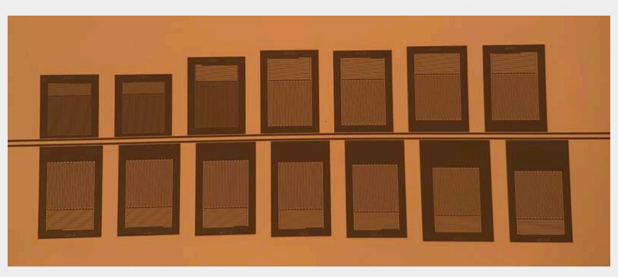
3. Fabrication and Measurement method

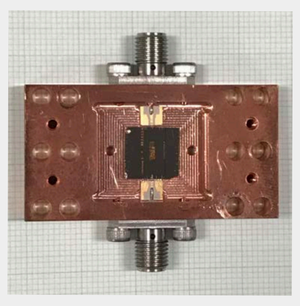
- **Substrate**
  Yttria-stabilized Zirconia (YSZ, Y_2O_3:$\mathbf{ZrO_2}$)
  $\longrightarrow$ New attempt as substrate material of KID
  Natural abundance of ^{94}Zr is ~17%.
  ZrO_2 is made stable at room temperature by doping Y_2O_3.
  10×10×0.5 mm^3 mono-crystal (orientation (100))
  Yttria concentration : 9.5 mol% and 20 mol%
  Thermal properties are Y conc. dependent[6].→ Impact on LEKID?

- **Design**
  14 LEKIDs with different performance
  - resonant frequency f_0 : 4.55 − 5.85 GHz (on Si substrate)
  - line width : 2 − 4 µm, resonator volume : 1843.8 µm^3
  - gaps between feed line and LEKID : 20 − 200 µm



- **Fabrication**
  Nb DC spattering → Photolithography → Nb dry etching
  Photolithography performed at Nanoscience Joint Laboratory.



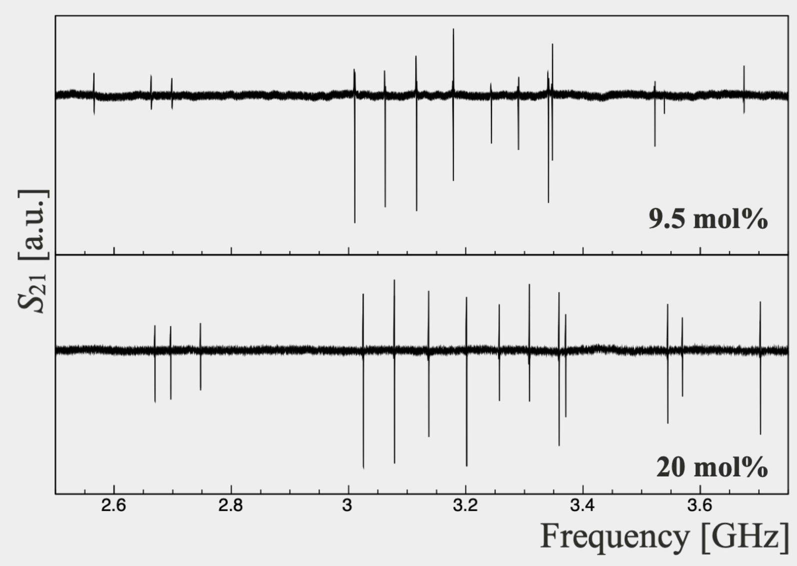


- **RF Measurement**
  - ^{3}He/^{4}He dilution refrigerator
    base temp. ~0.13 K
    (Critical temp. of Nb : 9.2K)
  - Vector Network Analyzer
    range: 10 MHz − 13.5 GHz

Dilution refrigerator

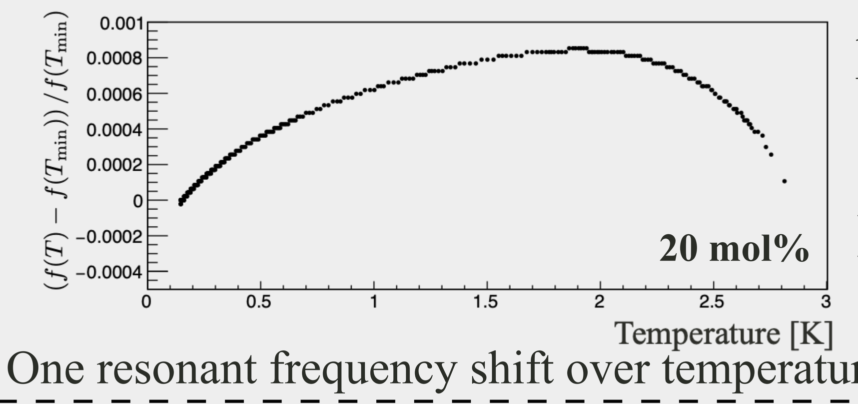
4. Result and Discuss

Both LEKIDs with Y9.5 mol% and 20 mol% were worked.
All resonant peaks (14/14) in transmittance S_{21} spectra were observed.



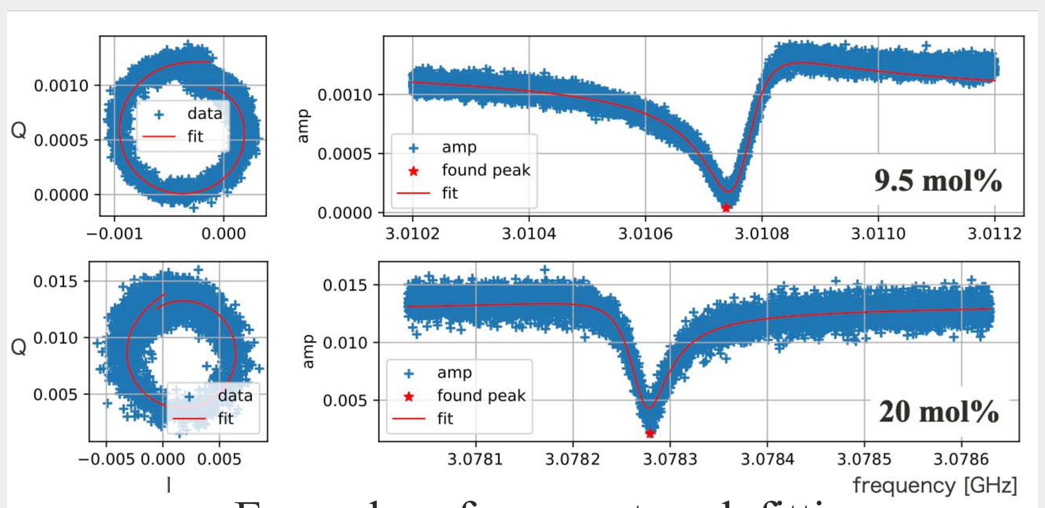
S_{21} spectra after smoothing and baseline subtracted

resonant frequency :
2.55 — 3.7 GHz
Not depend on Y concentration
Consistent frequency trend as
$f_0 \propto^{-1} \sqrt{\epsilon}$.
cf. Dielectric constant :Si 2.4, YSZ ~27



One resonant frequency shift over temperature

peaks detected @ < 3 K
Same shape in both Y concentration.
Inconsistent with Mattis-Bardeen model
⟶ RF loss[7]?? Kondo-effect[8]??



Examples of resonant peak fitting

Internal quality factor Q_i
~10^5 Order for both Y conc.
10 less than LEKID on Si
→ Impedance mismatching??
LEKID was designed for fabrication on Si substrates.

Y conc. of YSZ doesn't impact the frequency characteristics of LEKID.

5. Acknowledge and References

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The exposure process in photolithography was performed using a Maskless UV lithography system at Nanoscience Joint Laboratory of CEMS, RIKEN.

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