Development of Lumped Element Kinetic Inductance Detectors for Light Dark Matter Searches using Liquid Helium

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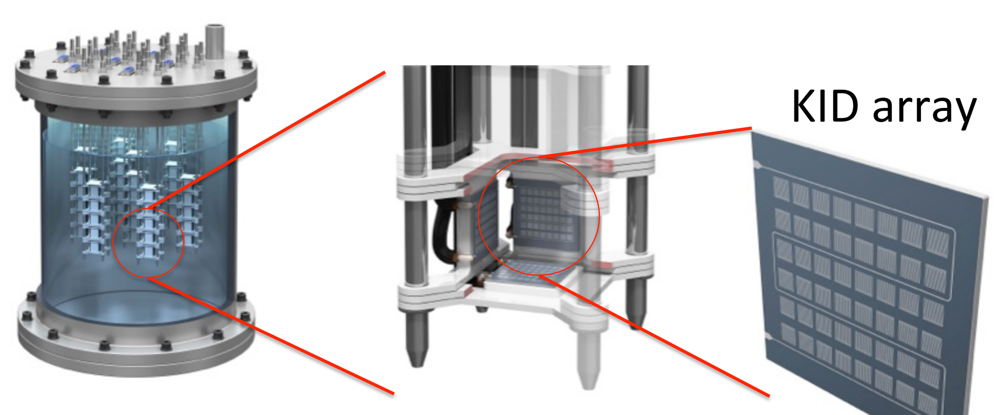
Abstract We have developed the superconducting detector LEKIDs (Lumped Element Kinetic Inductance Detectors) for a dark matter search using liquid helium. Helium may have sensitivity to the light WIMP mass less than 10 GeV/c^2. Recoiled helium atoms produce scintillation light photons with the wavelength of 80 nm (16 eV in energy). Those photons are detected with the superconducting detector LEKIDs.

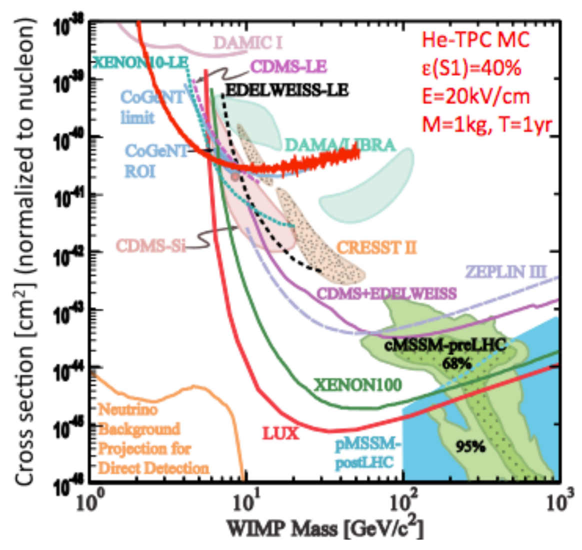
To understand the sensitivity of LEKID, it is important to measure the kinetic inductance fraction α. We have measured the value of α using temperature dependency of the resonant frequencies. Also, the LEKIDs have cross-talks among the resonators. It is necessary to reduce the cross-talks to less than 1%, while having an acceptance as large as possible. We have been developing an optimized LEKID design that has the cross-talks with the required level. We report the current status of the development of LEKIDs to satisfy our requirements.

Dark matter detectors

A direct search for light WIMPs (Weakly Interacting Massive Particles) with masses less than 10 GeV/c^2 has not been conducted intensively.
W. Guo and D.N. McKinsey proposed to use liquid He (LHe) for a light WIMP search; PRD 87, 15001 (2013).

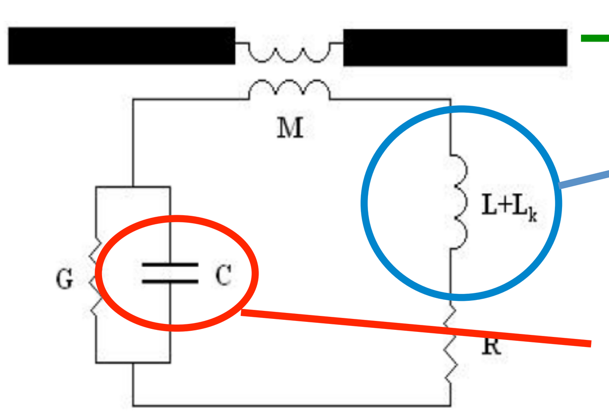
A WIMP may interact with helium, and recoiled helium atoms excite or ionize the surrounding helium.
Excited helium atoms produce 16 eV scintillation photons.
Ionized electrons are swept by an electric field, and emits 16 eV scintillation photons when the electrons are accelerated near the field wires.
The scintillation photons are detected using the surrounding LEKIDs.

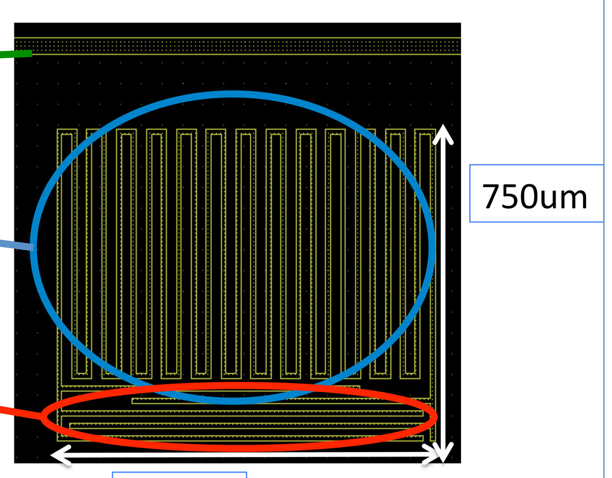




About the LEKID

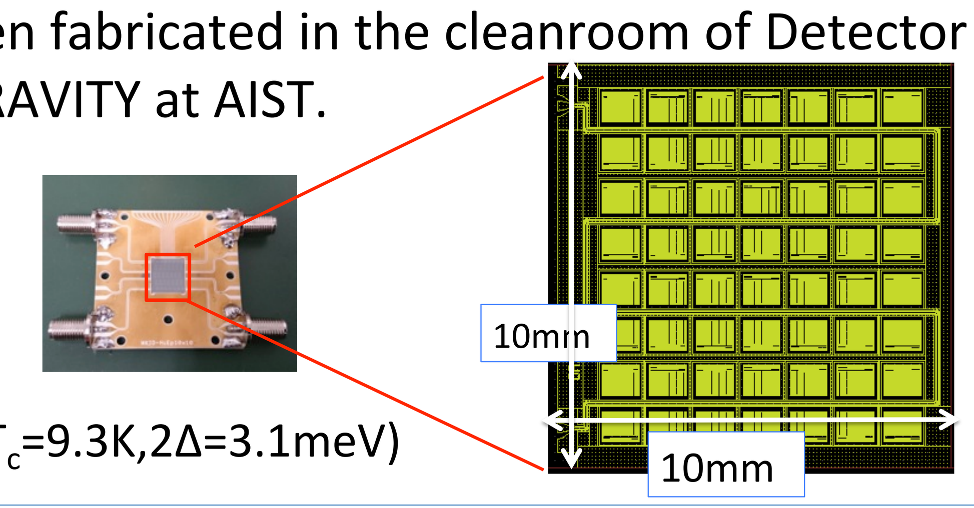
LEKID is a LC resonator consisting of an inductive meander and an interdigital capacitor.





S. Doyle et al., J. Low Temp. Phys. 151 (2008), 530-536.
P. K. Day et al., Nature 425 (2003) 817-820

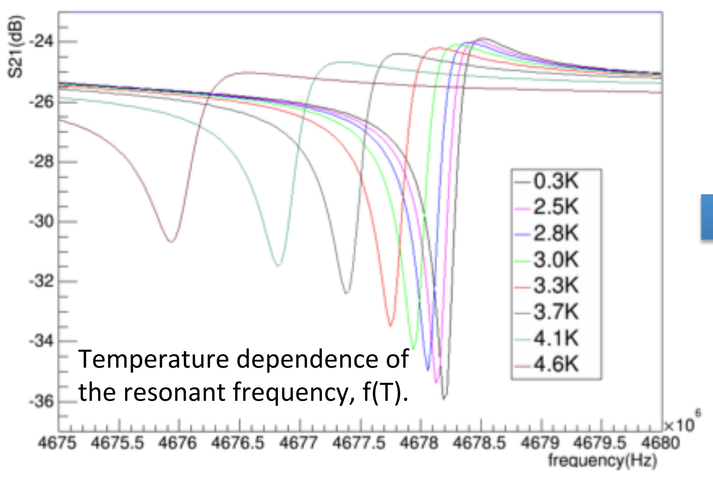
LEKIDs have been fabricated in the cleanroom of Detector Technology Project at KEK and in CRAVITY at AIST.

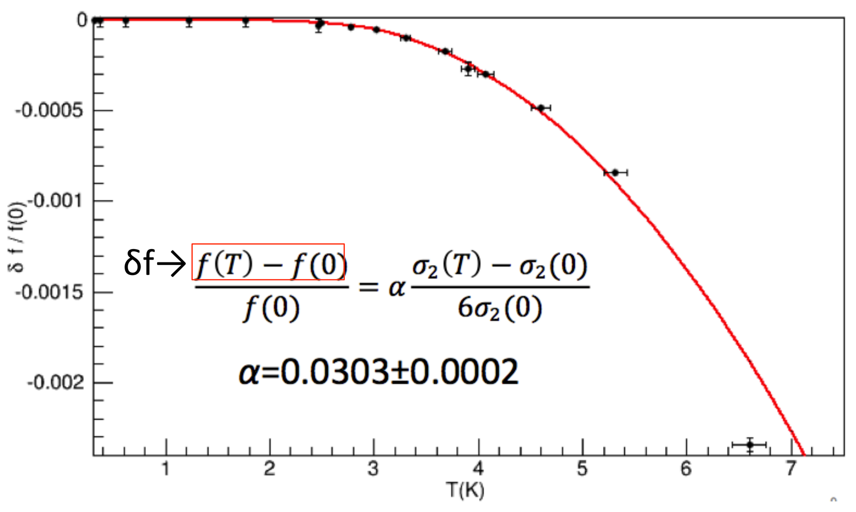


Status
56 pixel
Metal : Nb (T_c=9.3K,2Δ=3.1meV)

Temperature dependence measurement

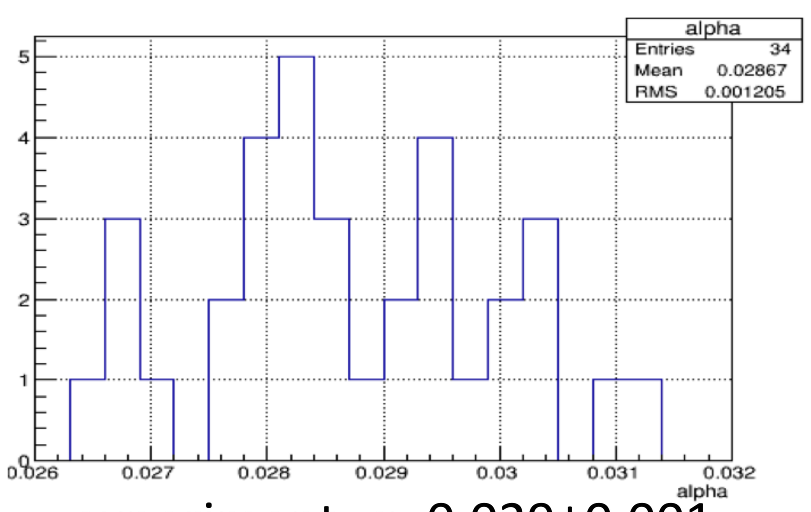
We measure temperature dependence of resonant frequency. We estimate values of α of our LEKIDs and compare it with SONNET simulation.





$$\delta f \rightarrow \frac{f(T)-f(0)}{f(0)} = \alpha\frac{\sigma_2(T)-\sigma_2(0)}{6\sigma_2(0)}$$

α=0.0303±0.0002



・experiment :α=0.029±0.001
・simulation :α=0.025
The measured results are comparable with estimation from the simulation.

SONNET simulation

We simulate resonant frequency with or without kinetic inductance by SONNET.

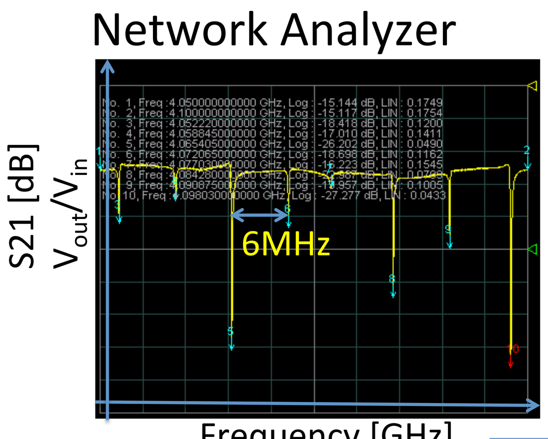
$$\omega_0 = \frac{1}{\sqrt{(L_k+L_g)C}} \quad \omega_0' = \frac{1}{\sqrt{L_g C}} \quad \frac{\omega_0}{\omega_0'} = \sqrt{\frac{L_g}{L_k+L_g}}$$

$$\alpha = \frac{L_k}{L_k+L_g} = 1-\left(\frac{\omega_0}{\omega_0'}\right)^2 \quad \alpha=0.025(\lambda_L=80\text{nm})$$

Cross-talks

The reasons of the non-uniformity of the frequency spacing:
1. Cross-talks among the resonators due to inductive and capacitive couplings.
2. Non-uniformity of the fabrication of resonators on the chip.

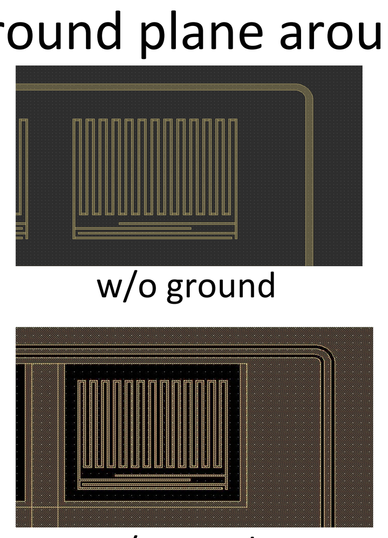
Measurement with a Vector Network Analyzer

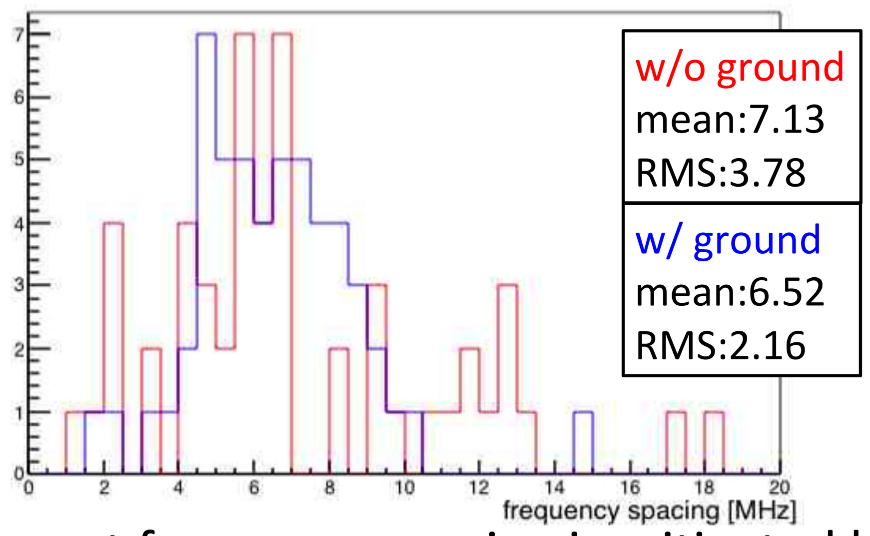


O. Noroozian et al., IEEE Trans. Micor. Theo. Tech. 60, 1235 (2012)

1.Cross-talks due to coupling

We have fabricated two types of the KID;
- without ground plane around the resonators
- with ground plane around the resonators.

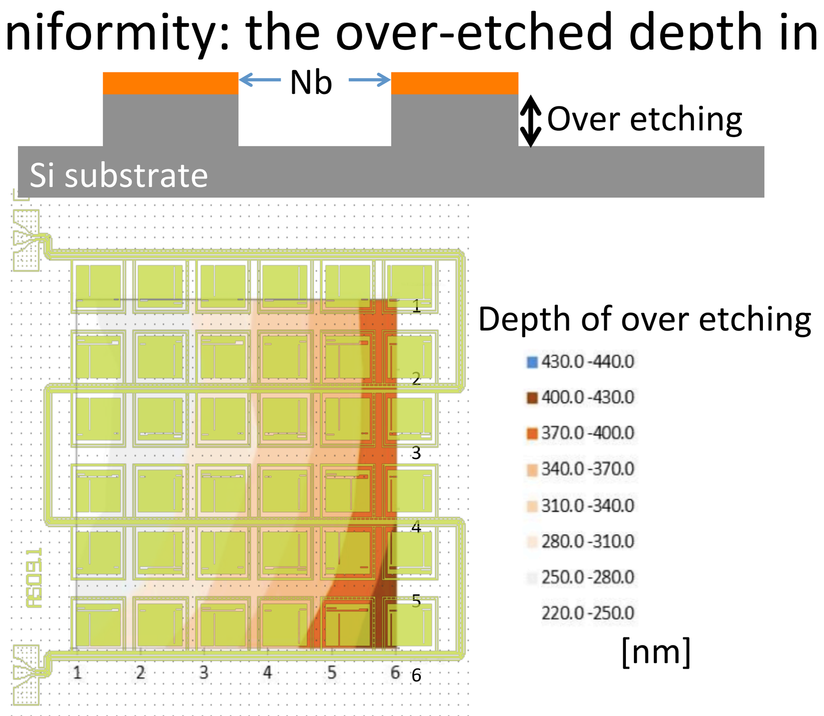


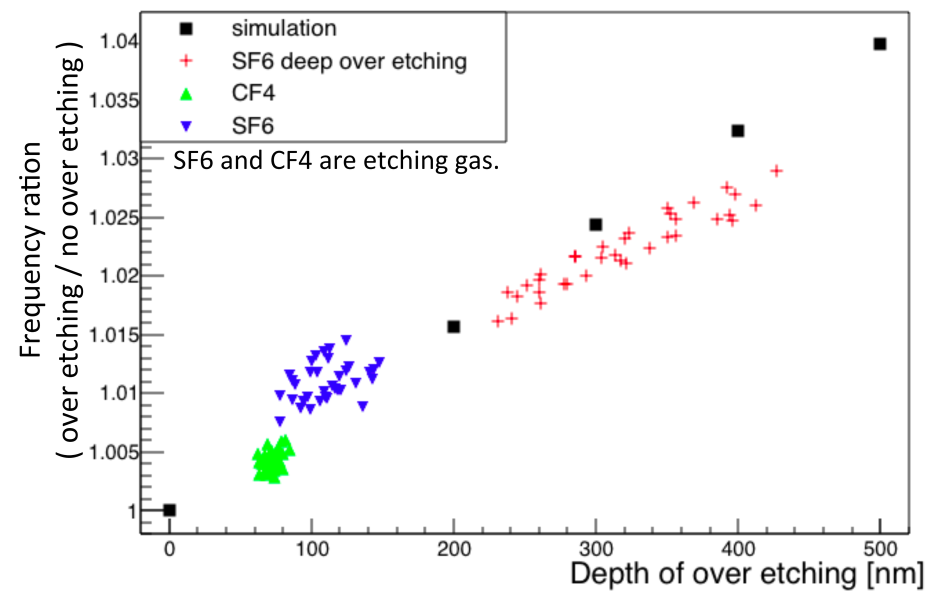


The non-uniformity of the resonant frequency spacing is mitigated by placing the ground shield around the resonators.

2.Over-etching effects

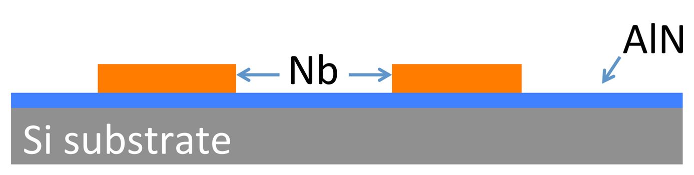
We have found the variation in freq. spacing is caused by the over-etching non-uniformity: the over-etched depth in the Si substrate depends on its position.

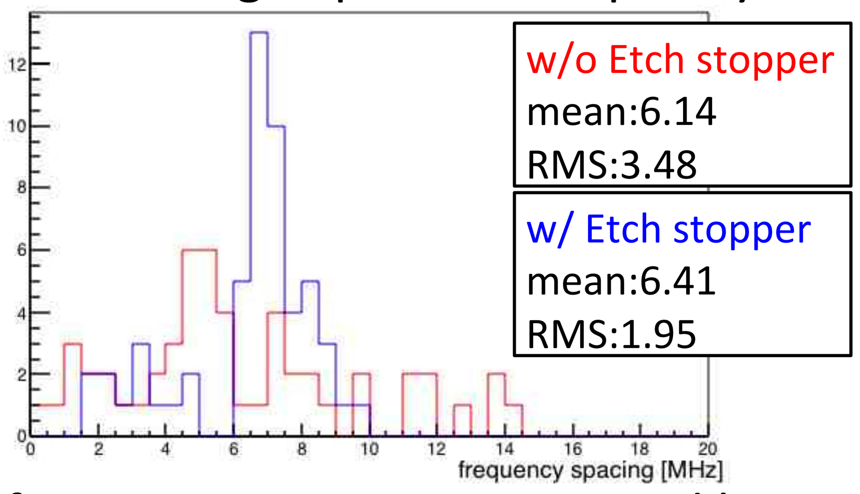




There is a clear correlation between the over-etching depth and frequency shift.

We form a thin AlN layer on the Si substrate to mitigate the over-etching.





The non-uniformity of the resonant frequency spacing is mitigated by the implementation of the etch stopper.

Summary

- We have been developing the superconducting detector, LEKID.
- From the measurements of the temperature dependence of the resonant frequencies, the measured α values are comparable with the simulation results.
- We have found the non-uniformity of the resonant frequency spacing is mitigated by
  - the ground shielding around the resonators
  - the implementation of the etch stopper.

Acknowledgements
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