Development of Superconducting Tunnel Junction Detector and Cold Amplifier for COBAND experiment

K.Takemasa[1], S.H.Kim[1], Y.Takeuchi[1], K.Nagata[1], K.Kasahara[1], S.Yagi[1] , R.Wakasa[1]
Y.Ootuka[1], S.Mima[2], K.Kiuchi[2], Y.Arai[3], I.Kurachi[3], M.Hazumi[3], H.Ishino[4],
T.Yoshida[5] , C.Asano[5] , Y.Kato[6], S.Matsuura[7], S.Kawahito[8], H.Ikeda[9], T.Wada[9], K.Nagase[9], S.Baba[9],
S.Shiki[10], M.Ukibe[10], G.Fujii[10], M.Ohkubo[10], E.Ramberg[11], M.Kozlovsky[11], P.Rubinov[11], S.B.Kim[12]

[1]Univ. of Tsukuba, [2]RIKEN, [3]KEK, [4]Okayama Univ., [5]Univ. of Fukui, [6]Kinki Univ.,
[7]Kanseigakuen Univ., [8]Shizuoka Univ., [9]JAXA/ISAS, [10]AIST, [11]Fermilab, [12]Seoul National Univ.

Motivation

- Difference between mass-squared of different generation neutrino has been measured by various experiment of neutrino oscillation.
- However, neutrino mass itself has not been measured.
- The COBAND(COsmic BAckground Neutrino Decay search) experiment measure the neutrino mass by observing the neutrino decay.

Neutrino decay is a radiative decay in which a lighter neutrino and a photon are emitted from a heavier neutrino.

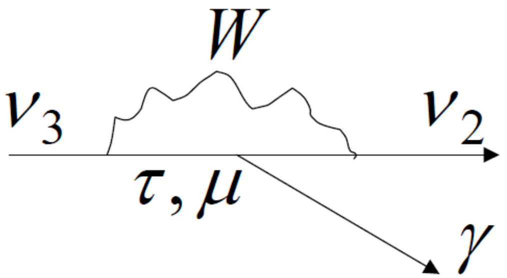
$$\nu_3 \rightarrow \nu_2 + \gamma$$

Energy of the photon is given below

$$E_\gamma = \frac{\Delta m_{32}{}^2}{m_3}$$

Measured by various experiments of neutrino oscillation ($2.4 \times 10^{-3}\ eV^2$)

we'll measure this.



Feynman diagram of neutrino decay

- → We can obtain neutrino mass itself.

Energy spectrum of cosmic background neutrino decay and it's background

- Lifetime of neutrino is very long(>10^{12}year) , to observe ν decay, we need immense quantity of neutrino.
- Most promising method is to observe the decay of cosmic background neutrino(CBN).
  - CBN has a temperature of 1.9K and a particle density ρ of 110 cm^{-3} per generation.

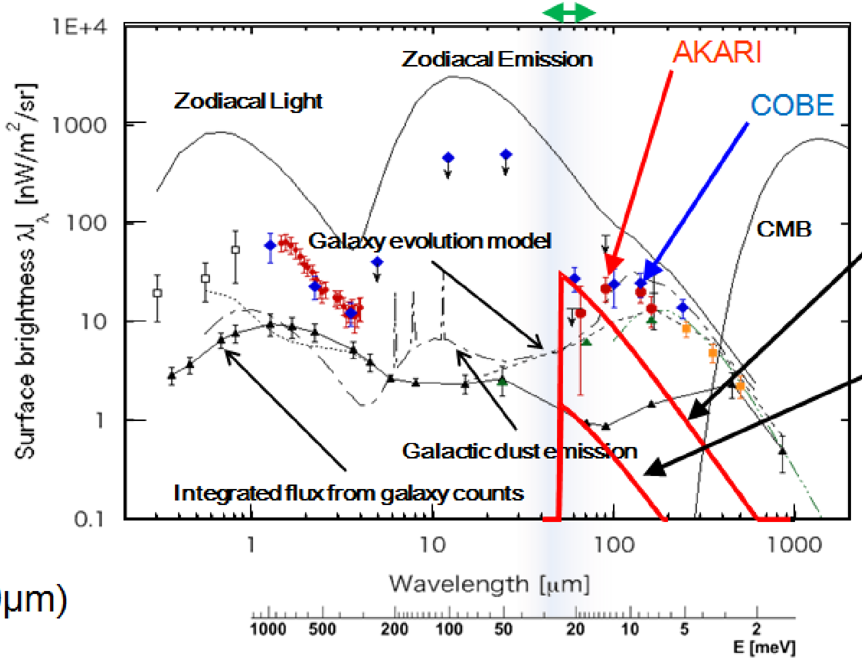
Background

Zodiacal Emission
λI_λ~500nW/m²/sr

CIB (COBE)
λI_λ~30nW/m²/s

at $E_\gamma = 25\mathrm{meV}$ (λ = 50μm)

Rocket experiment coverage (λ = 40 ~ 80μm)



Expected E_γ spectrum
$m_3 = 50\mathrm{meV}$

ν-decay ($\tau = 5 \times 10^{12}$yr)
λI_λ~30nW/m²/s

ν-decay ($\tau = 1 \times 10^{14}$yr)
λI_λ~1.5nW/m²/s

ν-decay ($\tau = 1 \times 10^{17}$yr)
λI_λ~1.5pW/m²/s

By measuring the energy spectrum of the Zodiacal Emission with the CBN decay continuously, we can see the CBN decay signal as a high energy cutoff.
To identify the shape edge, we need detector which has better than 2% resolution for E_γ ~ 25meV(λ~50μm)

The COBAND experiment

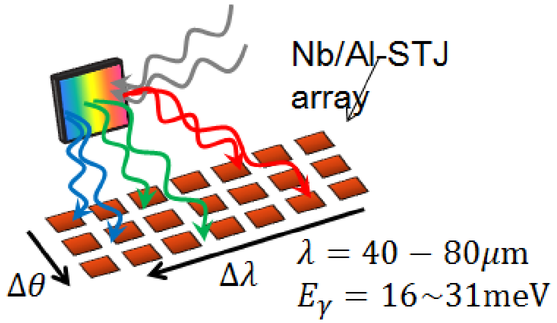
The COBAND experiment consists of two types of measurements:

- **Rocket experiment**
  - 200sec data acquisition at 200km height in 2019 in earliest.
  - Improve the current limit of lifetime τ(ν3) by two orders of magnitude ($\sim 10^{14}$years).
  - Detector: Array of 50 Nb/Al–STJ pixels with diffraction grating covering $\boldsymbol{\lambda = 40-80\mu m}$

    Nb/Al–STJ has poor resolution for identify signal cutoff, but counting is possible.

- **Satellite experiment after 2020**
  - 100days measurement at satellite
  - Expected sensitivity: τ(ν3) ~ 10^{17}year
  - Detector: STJ detector using Hafnium(Hf–STJ)

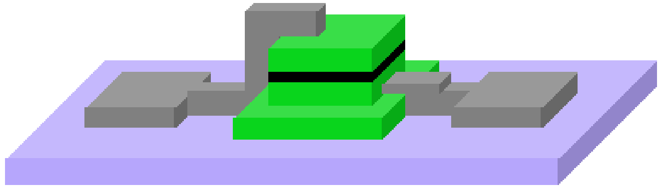
    Hf–STJ achieves 2% energy resolution if fano factor <0.3



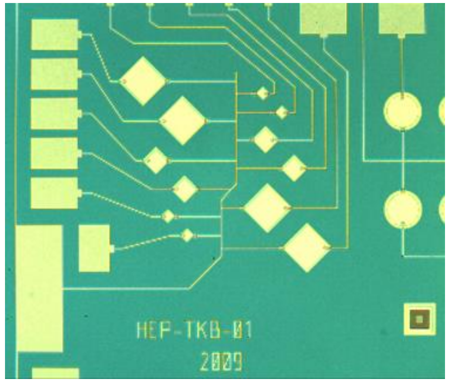
We are developing Nb/Al–STJ and Hf–STJ for these two experiments.

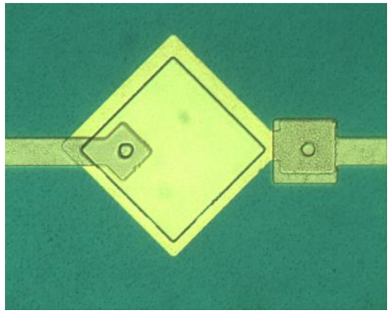
STJ (Superconducting Tunnel Junction) Detector

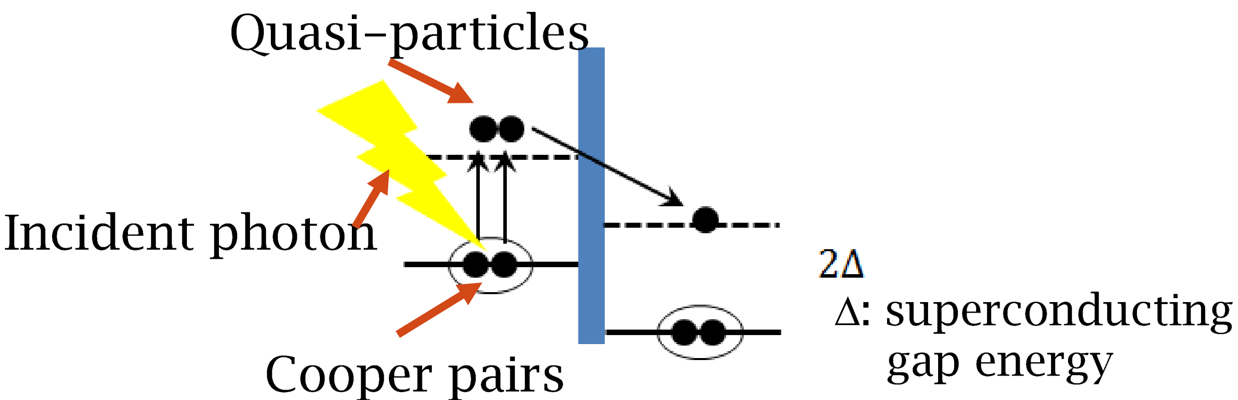
- **Structure**
  - STJ is a type of Josephson junction composed of Superconductor/Insulator/Superconductor
  - Size: dozens~hundreds μm square and 500 nm height
- **Working principle**
  - Incident photon is absorbed in the superconductor and excites cooper pairs.
  - Excited cooper pairs become quasi-particles.
  - Quasi-particles go through insulator by tunnel effect.
  - Number of quasi-particles is determined by energy of incident particle.
  - Thus, we can measure the energy of incident particle by measuring the tunnel current.

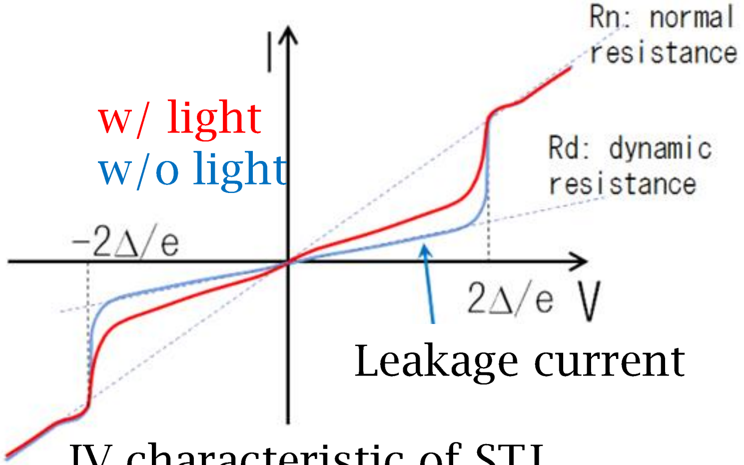


Overhead view of STJ detector









IV characteristic of STJ

Energy resolution of STJ detector

- Statistical fluctuation in number of quasi-particles determines STJ energy resolution.
- Smaller superconducting gap energy Δ yields better energy resolution.

$$\sigma_E = \sqrt{(1.7\Delta)F\varepsilon}$$

Material	Tc(K)	Δ(meV)
Niobium	9.20	1.550
Aluminum	1.14	0.172
Hafnium	0.13	0.021

Δ: Superconducting gap energy
F: fano factor
ε: Photon energy

Tc : Superconducting critical temperature
Need ~1/10Tc for practical operation

Nb

- Well established as Nb/Al-STJ
- $N_{q.p.} = 25meV/1.7\Delta = 9.5$
- poor resolution but counting is possible

Hf

- Hf-STJ as a photon detector is not established
- $N_{q.p.} = 25meV/1.7\Delta = 735$
- 2% energy resolution is achievable if fano factor <0.3

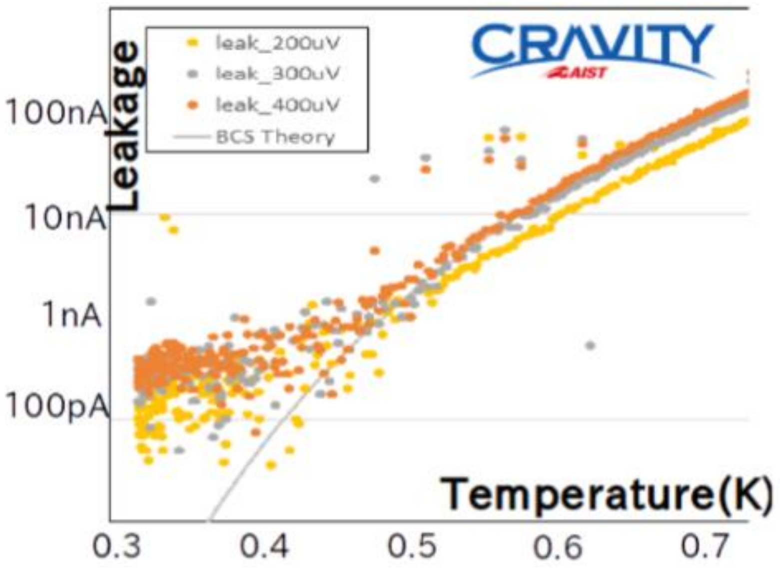
Development of Nb/Al-STJ

Performance of our Nb/Al-STJ sample

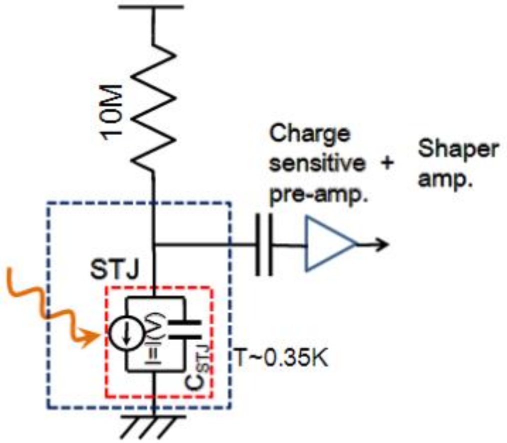
Our Nb/Al-STJ is fabricated with CRAVITY at AIST

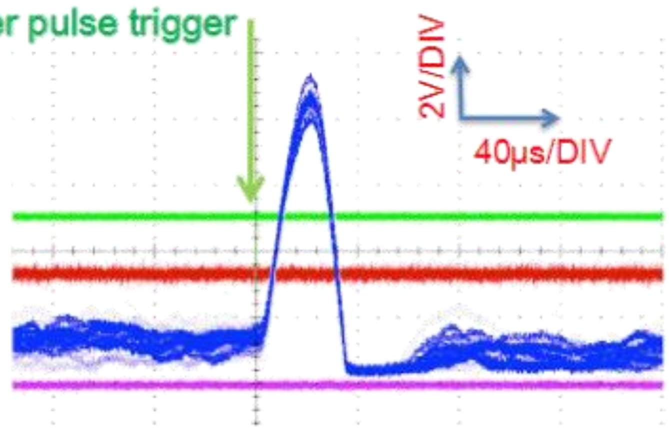
Structure: Nb/Al/AlOx/Al/Nb = 100nm/70nm/1nm/70nm/200nm

- **Leakage current**
  - Requirement: $I_{leak} < 100pA$
  - Measured: I_{leak} at temperatures below 400mK
    ~ 200pA (50μm×50μm sample)
    ~ 50pA (20μm×20μm sample)



- **Frequency response**
  - Requirement: faster than 400Hz = 2.5ms



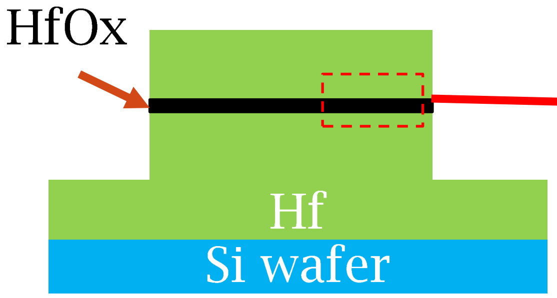


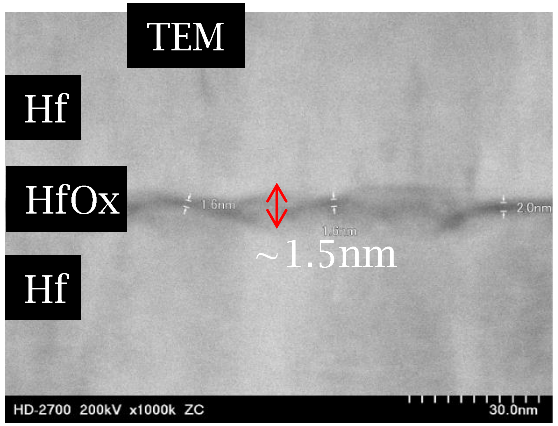
Response to 465nm laser
(using charge sensitive pre-amp. and shaper amp.)
~10 photons are detected

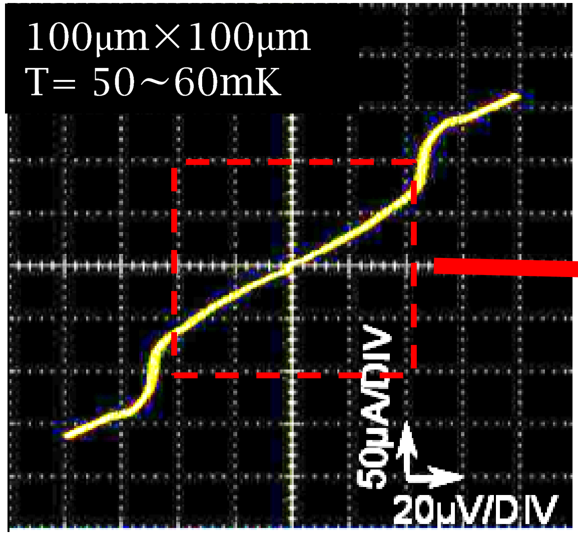
Development of Hf-STJ

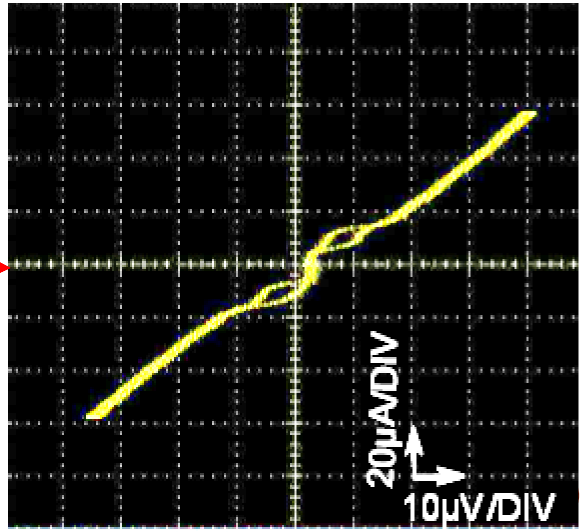
- Earlier version of our Hf-STJ
  - Structure: Hf/HfOx/Hf = 250nm/1.5nm/300nm
  - Δ ~ 20μeV
  - Leakage current at 20μV ~ 20μA@50mK (100μm×100μm sample)

Leakage current is too large.
Required leakage current at 20μV= 10pA@50mK
Necessary to perform improvements very much.



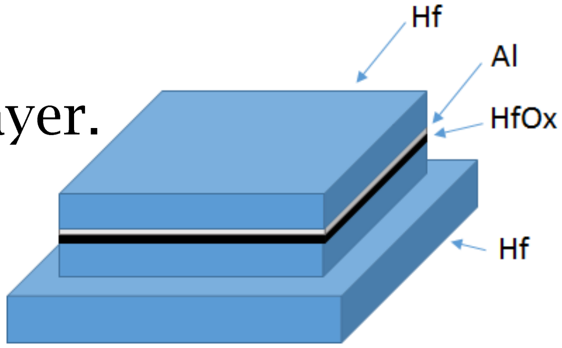


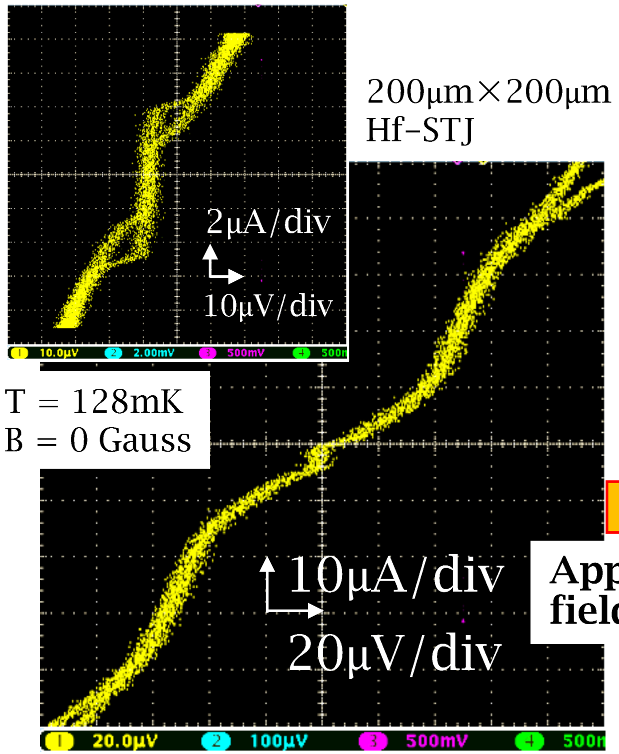




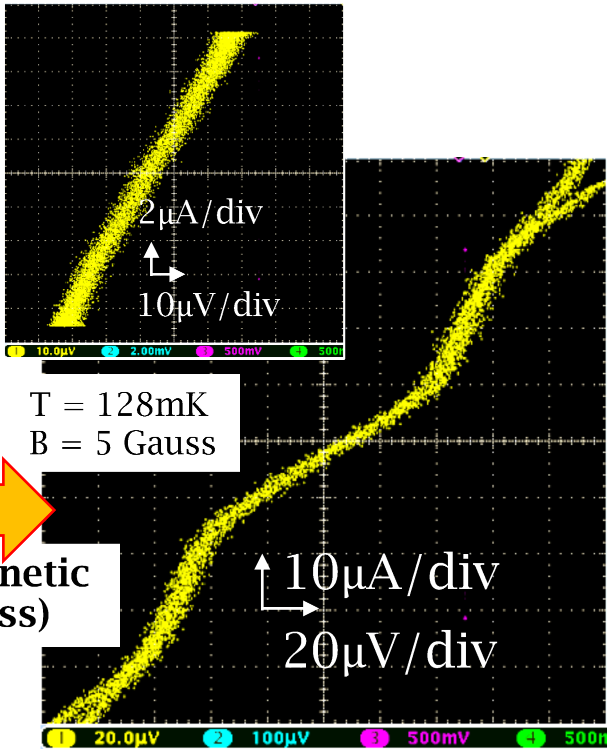
Development of Hf-STJ

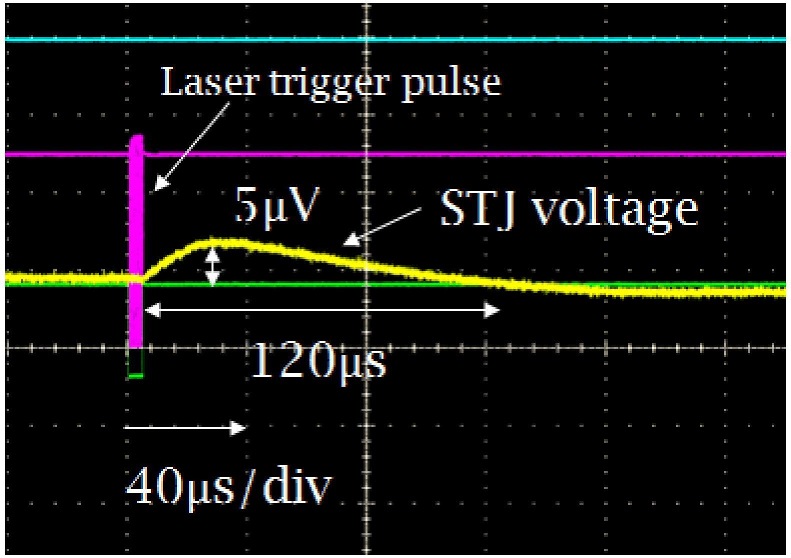
- To reduce leakage current, we review the structure of Hf-STJ.
- We add thin (a few nm) Al layer between the insulator and the upper Hf layer.
  - Josephson current is observed and it's suppressed by magnetic field.
  - Δ = 20~30μeV. This value is about same value as earlier Hf-STJ.
  - I_{leak} at 20μeV = 5μA@128mK (200μm × 200μm sample)
    - I_{leak} becomes 4 times smaller than old sample. (considering size influence, 16times smaller)
    - But I_{leak} is still large. (Required I_{leak} at 20μeV = 30pA@120mK)





Apply magnetic field(5 Gauss)





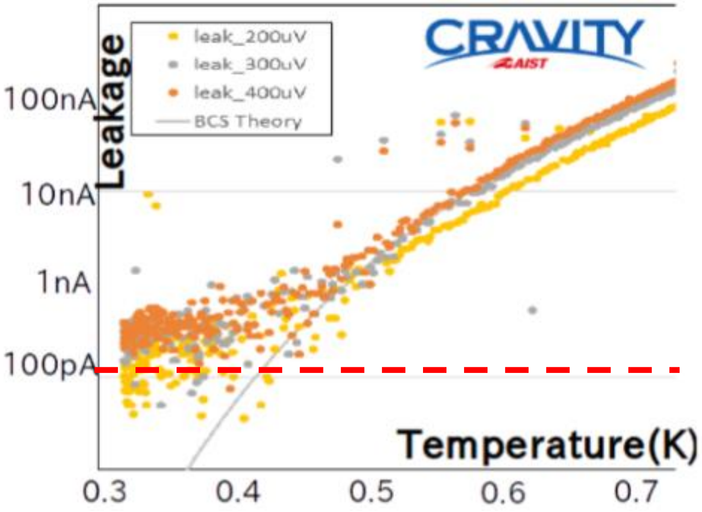
Response to laser pulse

- 465nm laser
- 5MHz oscillation 5μs per 100ms.

Development of cold amplifier

- Our Nb/Al–STJ achieves the requirement.
- But, we haven't succeeded in detecting a far infrared single photon due to readout noise.
- To improve the signal–to–noise ratio, we are developing cold amplifier.

- Requirements for cold amplifier
  - **Operation at cryogenic temperature**
    - Requirement for leakage current of Nb/Al–STJ is below 100pA
    - To reduce thermal excitation($\propto \sqrt{T}\, e^{(-\Delta/k_bT)}$), we need to make cooler 300mK.
    - Cold amplifier should be able to operate at 300mK.
  - **Low power consumption**
    - Typical cooling power of our refrigerator is 100μW@300mK.
    - Power consumption of the amplifier should be as low as possible.
  - **Response speed**
    - The integration time of charge is a few μs.
    - Amplification gain should be large enough up to 1MHz.

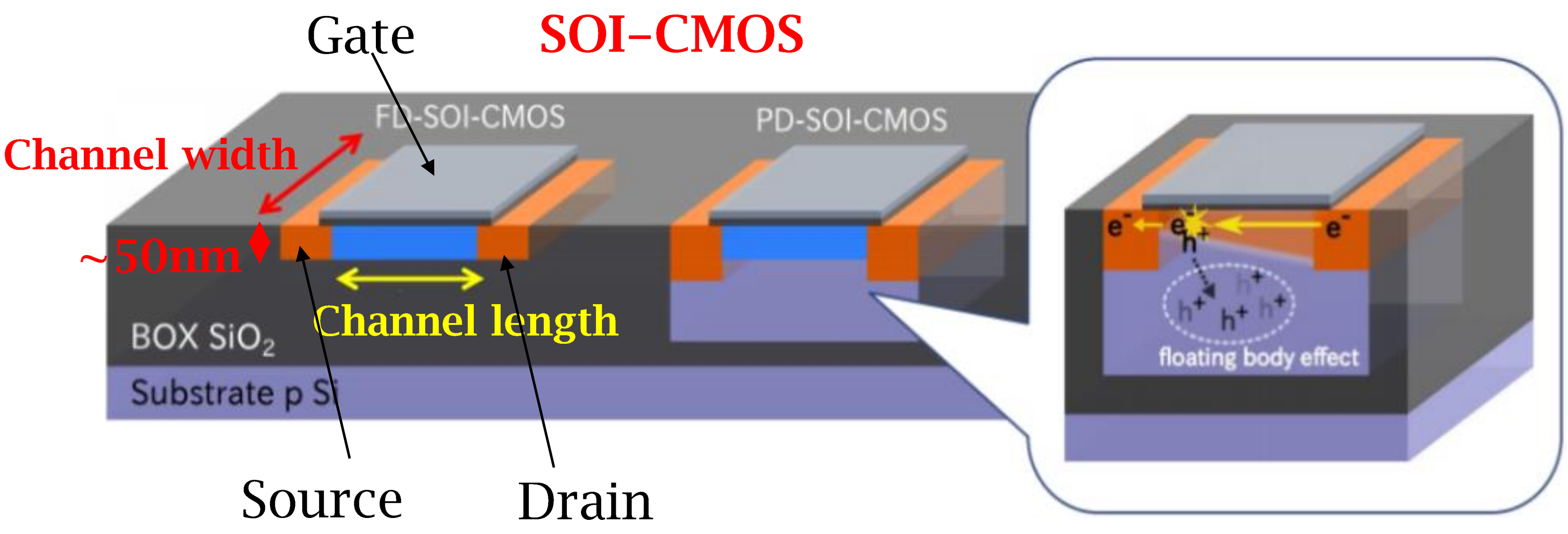


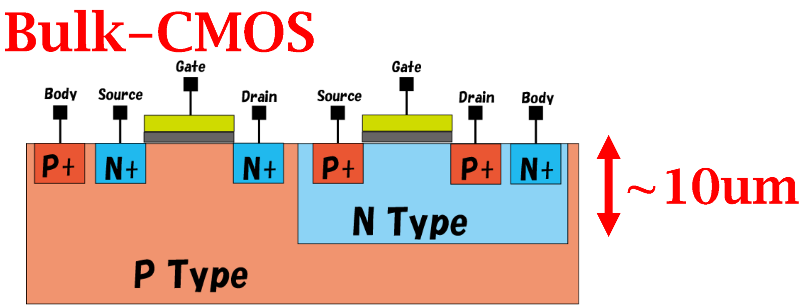
Leakage current of Nb/Al–STJ

→ Cold amplifier using SOI(Silicon–On–Insulator) technology can achieve these requirements

SOI (Silicon-On-Insulator) device

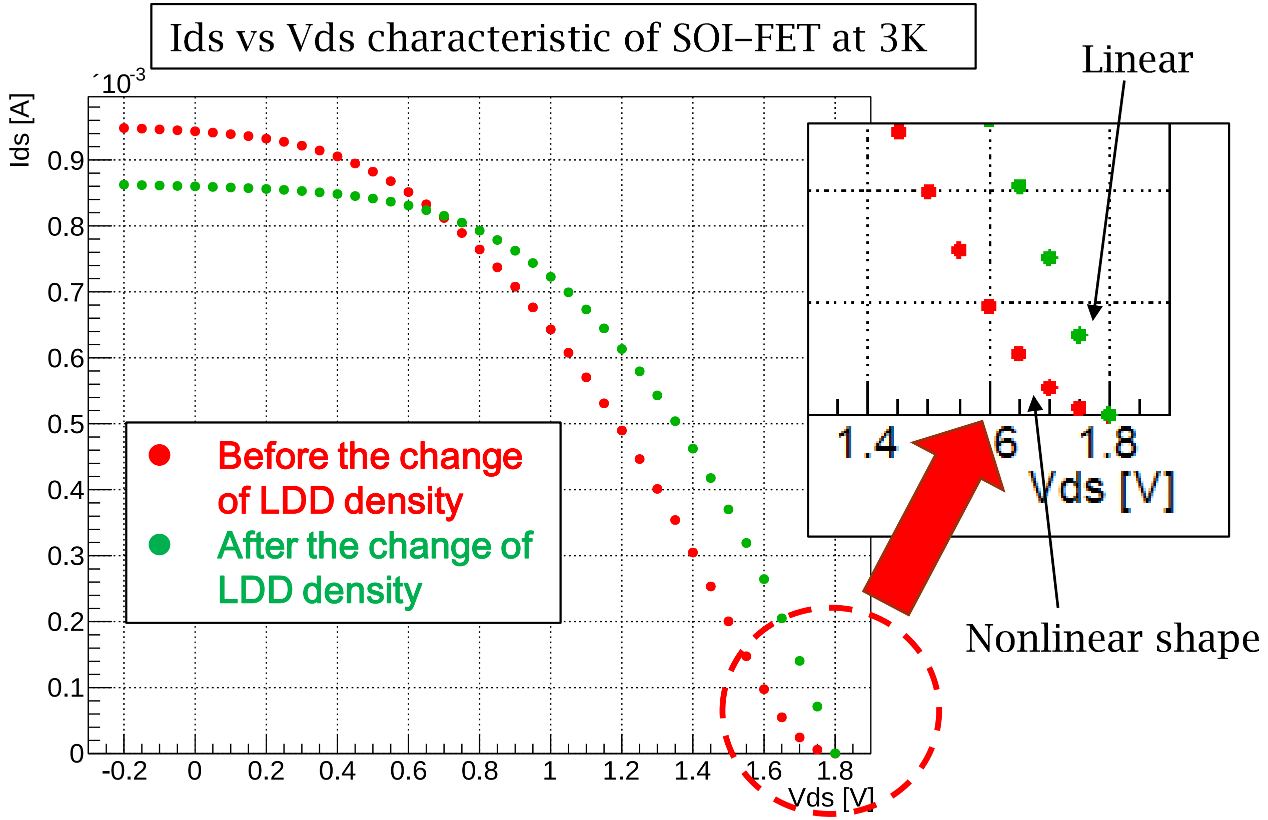
- SOI device consists of devices on silicon thin film that exists on insulating film.
  - FD(Fully depleted) SOI: thin SOI layer(normally<50nm). All body areas under the channel are depleted.
- FD-SOI device was proved to operate at 4.2K by a JAXA group.
- Characteristics:
  - Low power consumption
  - High speed
  - Easy large scale integration
  - Suppression of charge-up by high mobility carrier due to thin depletion layer(~50nm)



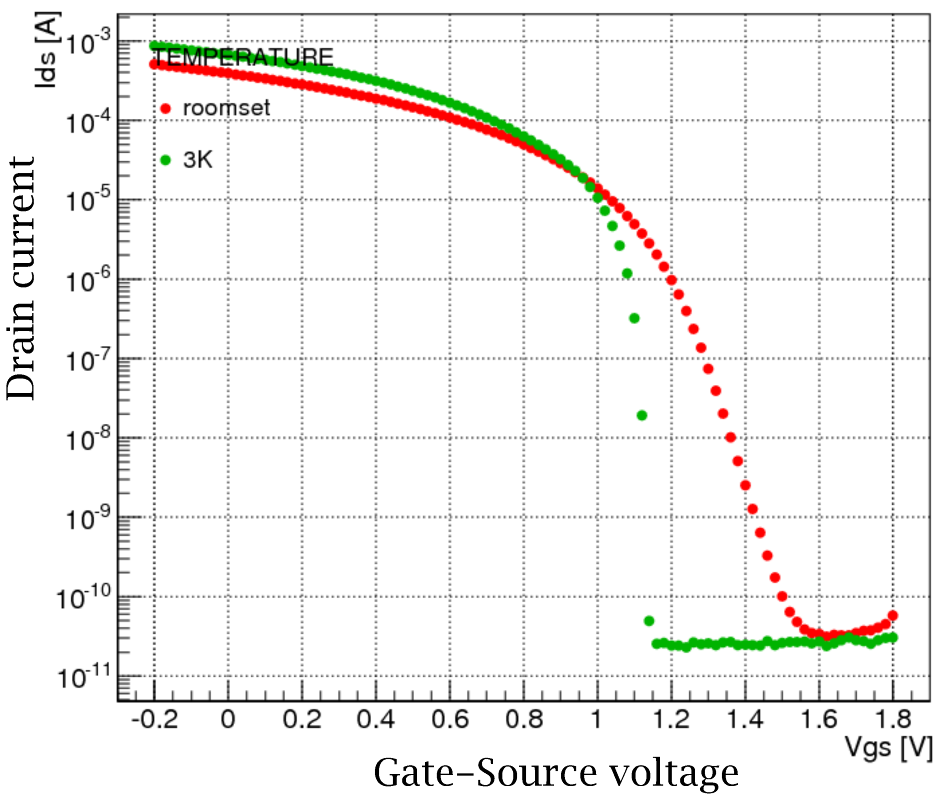


Characteristics of SOI–FET at cryogenic temperature

- We measured characteristics of SOI–FET at cryogenic temperature.
  - I_{ds}–V_{ds} curve shows a nonlinear shape in liner region.
  - It's improved by the changing LDD(Lightly Doped Drain) density.
  - Threshold voltage become small at cryogenic temperature. (this is not matter)
- SOI–FET works well at cryogenic temperature.

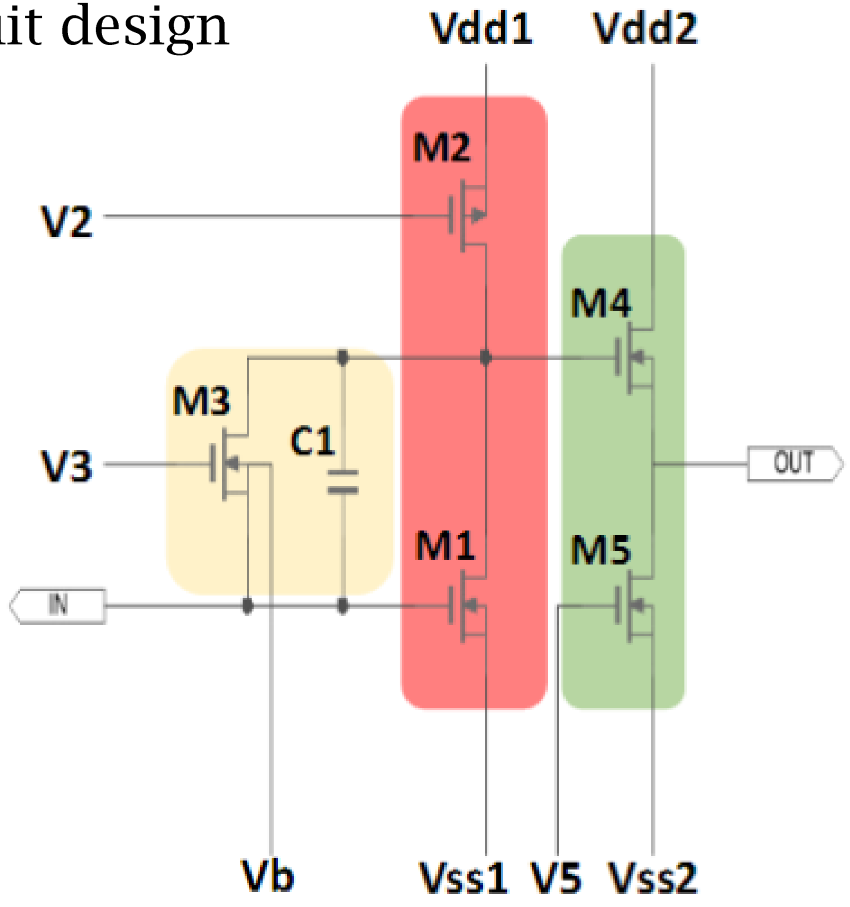


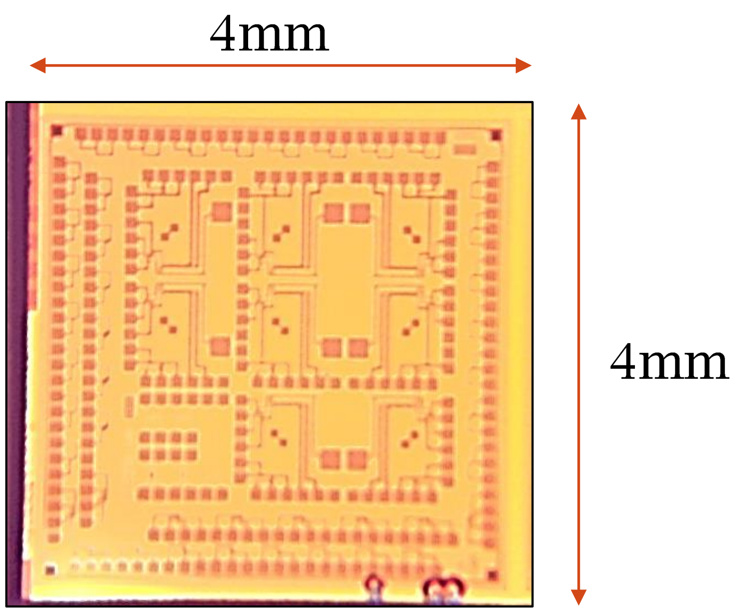
Ids vs Vgs characteristic of SOI–FET



SOI cold pre-amplifier

- Circuit design





Common source amp.

Feedback circuit

stabilizes bias voltage of common source amp.

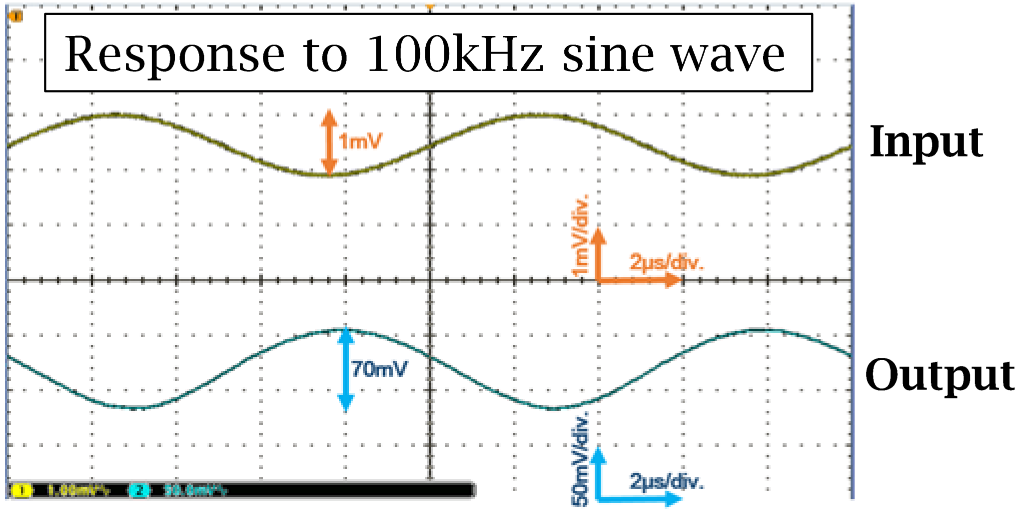
Buffer circuit

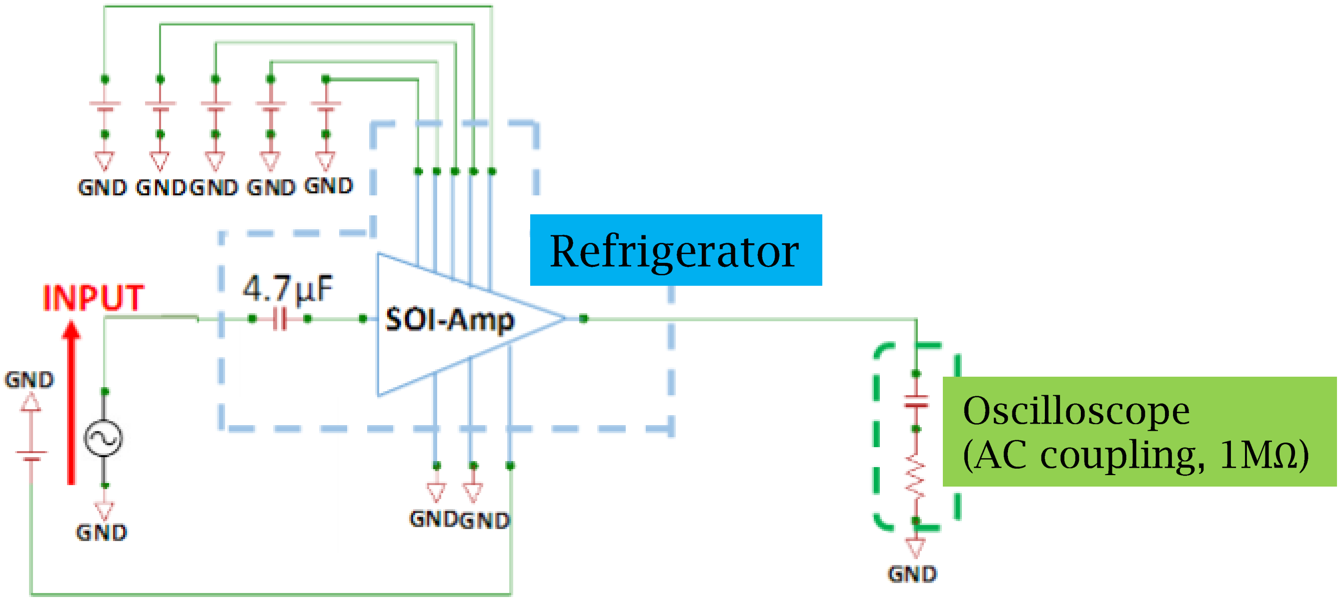
makes output impedance smaller

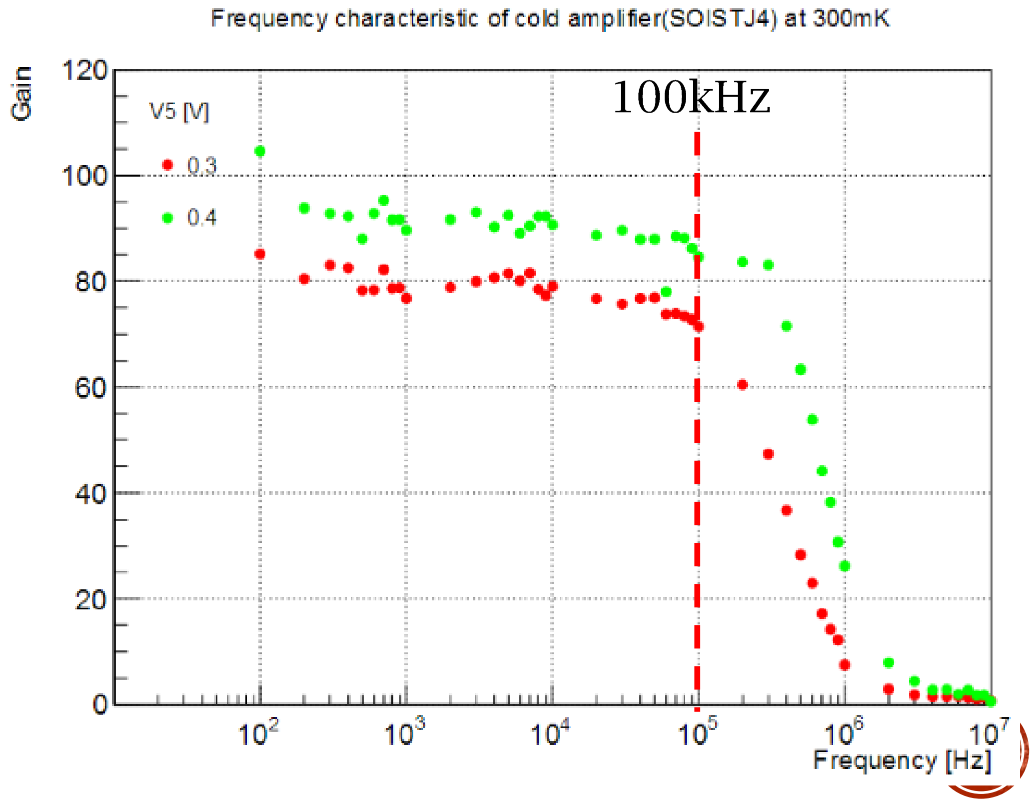
	Type	W [μm]	L [μm]
M1	Nch-CLst2	40	1
M2	Pch-CLst2	1	10
M3	Nch-CLst2	1.6	10
M4	Nch-CLst2	70	1
M5	Nch-CLst2	60	1
C2	MIM cap.	100 fF	

Frequency characteristics of SOI cold pre-amplifier

- Input: sine wave, 1mV$_{pp}$
- SOI pre-amp shows a gain of 80 at frequencies below 100kHz
  - Gain of 30 at frequency of 1MHz
- Power consumption: 230μW
  - This value is above the cooling power of 300mK stage(100μW) of our refrigerator.
  - We are considering moving preamp from 300mK stage to 3K stage(cooling power: 250mW).







Summary

- We can determine neutrino mass or renew neutrino lifetime lower limit by COBAND(cosmic background neutrino decay search) experiment.
- We are developing STJ detectors to detect a single far-infrared photon in energy range between 15 and 30meV for the COBAND experiment.

- Nb/Al-STJ achieves the leakage current requirement for the COBAND experiment.
- Leakage current of Hf-STJ is improved and Hf-STJ's response to the visible light was observed.
  - However, Hf-STJ hasn't exhibited an enough performance for the COBAND experiment due to it's large leakage current.
- FD-SOI cold amplifier is able to work at cryogenic temperature of 300mK and it shows excellent performance.