B02

R&D status of Hf-STJ

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For COBAND collaboration

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Motivation

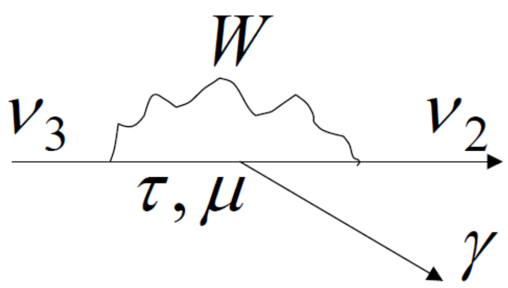
- Difference between mass-squared of different generation neutrino has been measured by various experiments of neutrino oscillation.
- However, neutrino mass itself has not been measured.
- The COBAND(COsmic BAckground Neutrino Decay search) experiment measure the neutrino mass by observing the neutrino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

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



Feynman diagram of neutrino decay

- → We can obtain neutrino mass itself.

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

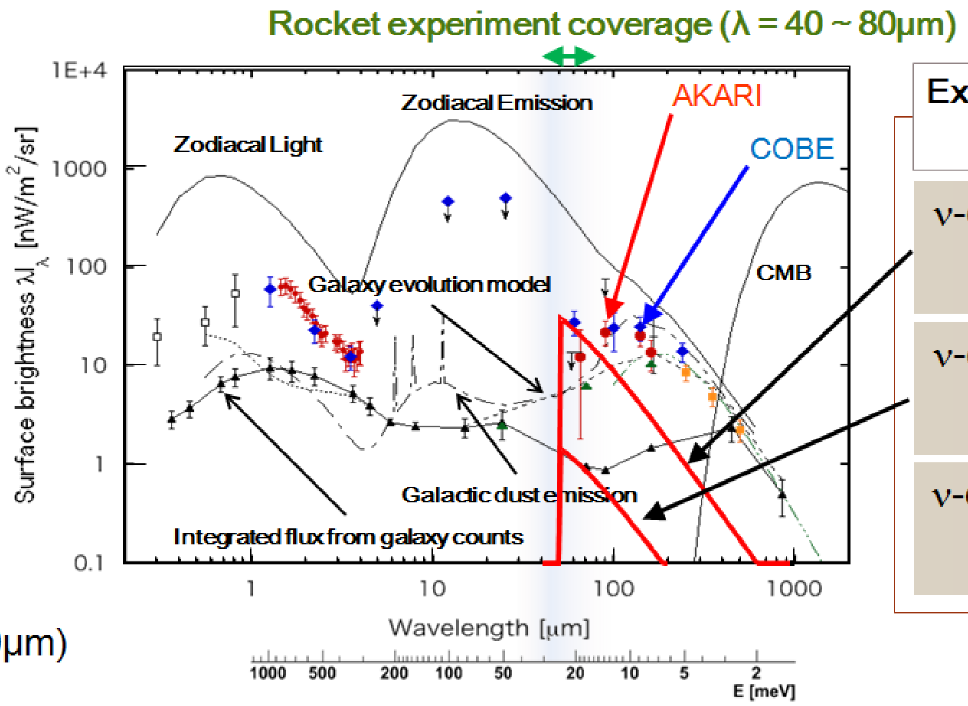
- Lifetime of neutrino is very long($\tau_3 > 10^{12}$year, J.Phys.Soc.Jpn.81,024101(2012)), to observe ν decay, we need an immense number of neutrino.
- Most promising method is to observe the decay of cosmic background neutrino(CBN).
  - CBN has a temperature of 1.9K and a particle density ρ of 110 cm^{-3} per generation.

Background

Zodiacal Emission
λI_λ~500nW/m²/sr

CIB (COBE)
λI_λ~30nW/m²/s

at $E_\gamma = 25$meV (λ = 50μm)



Expected E_γ spectrum
$m_3 = 50$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

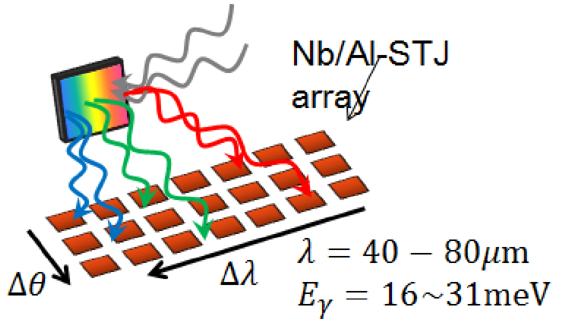
By measuring the energy spectrum of the Zodiacal Emission with the CBN decay continuously, we can see the CBN decay signal as a high energy cutoff.
To identify the shape edge, we need detector which has better than 2% resolution for E_γ ~ 25meV(λ~50μm)

The COBAND experiment

The COBAND experiment consists of two types of measurements:

- **Rocket experiment**
  - 200sec data acquisition at 200km height in 2019 in earliest.
  - Telescope: diameter:15cm, view angle: 0.006° ×0.05°
  - Improve the current limit of lifetime τ(ν3) by two orders of magnitude (~10^{14}years).
  - Detector: Array of 50 Nb/Al-STJ pixels with a diffraction grating covering $\boldsymbol{\lambda = 40-80\mu m}$

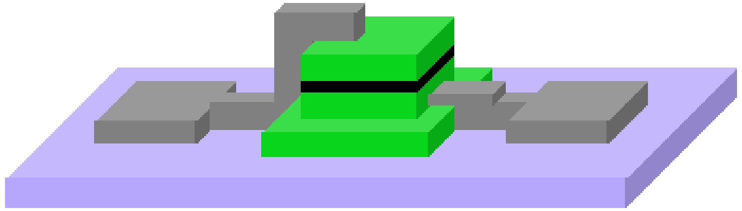
    Nb/Al-STJ has poor resolution for identify signal cutoff, but counting is possibl



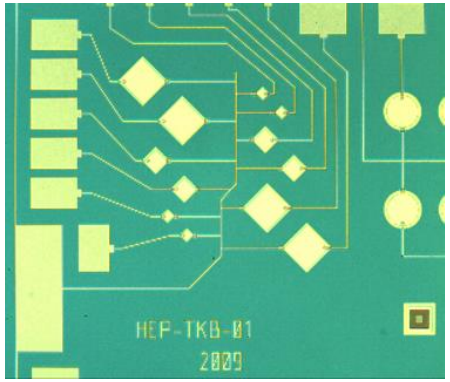
- **Satellite experiment after 2020**
  - 100days measurement at satellite
  - Telescope: diameter:20cm, view angle: 0.1°
  - Expected sensitivity: τ(ν3) ~ 10^{17}year
  - Detector: STJ detector using Hafnium(Hf-STJ)

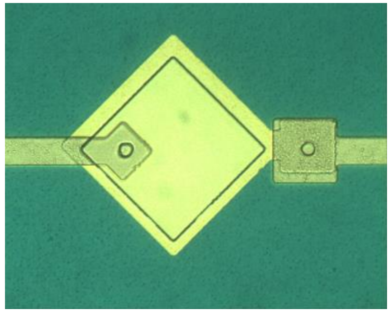
STJ (Superconducting Tunnel Junction) Detector

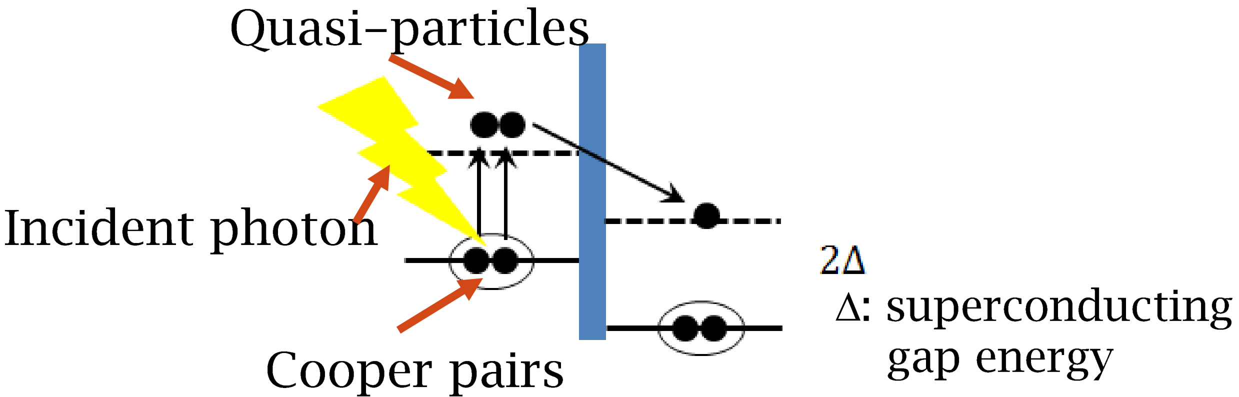
- **Structure**
  - STJ is a type of Josephson junction composed of Superconductor/Insulator/Superconductor
  - Size: dozens~hundreds μm square and 500 nm height
- **Working principle**
  - Incident photon is absorbed in the superconductor and excites cooper pairs.
  - Excited cooper pairs become quasi-particles.
  - 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.

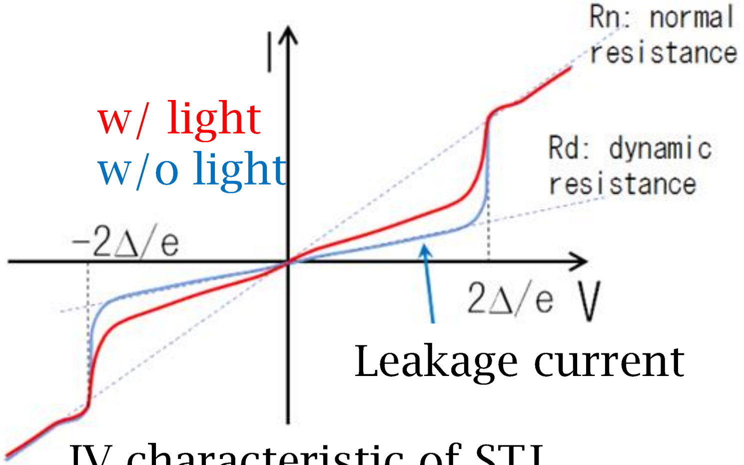


Overhead view of STJ detector









IV characteristic of STJ

Energy resolution of STJ detector

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

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

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

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

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

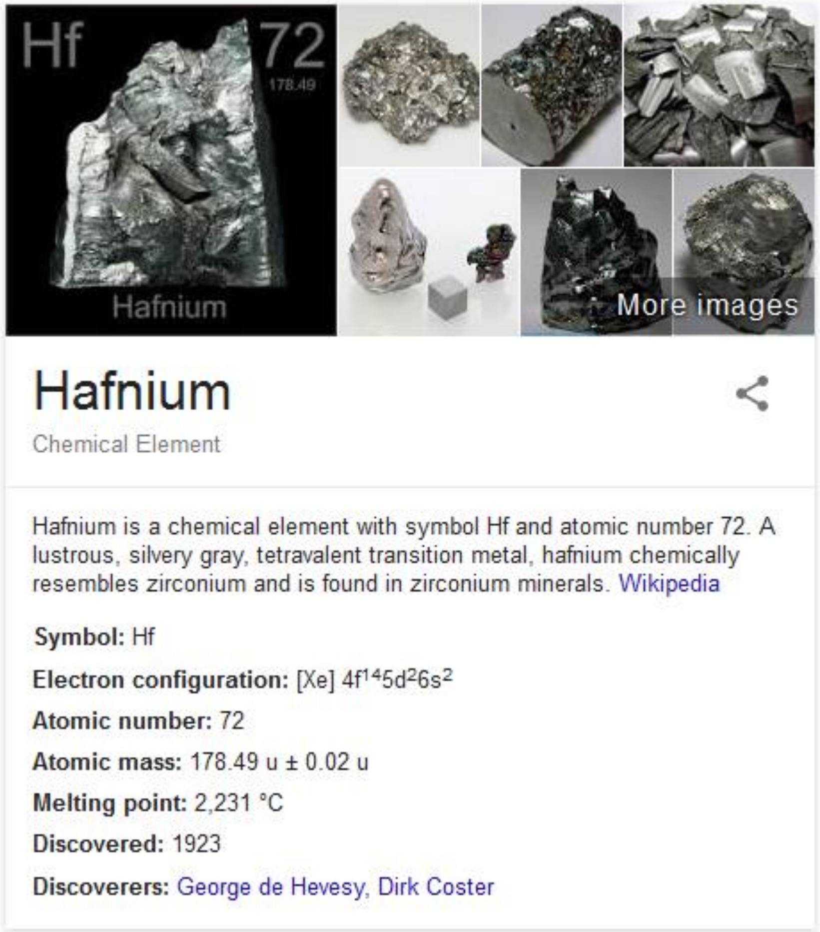
Nb

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

Hf

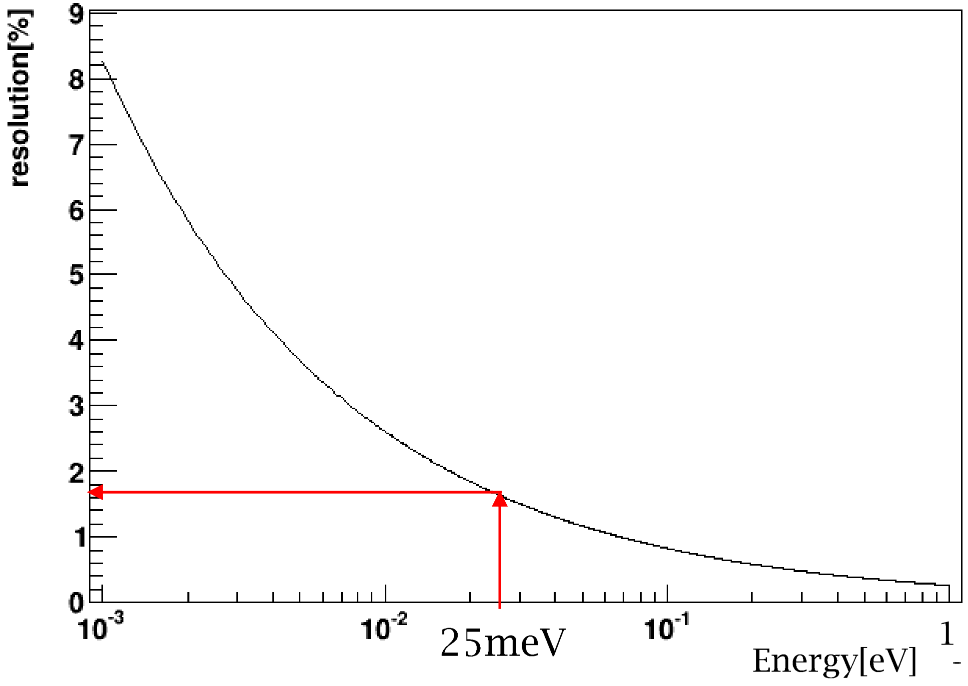
- Hf-STJ as a photon detector is not established
- $N_{q.p.}$ = 25meV/1.7Δ =735
- 2% energy resolution is achievable if fano factor <0.3

Hf-STJ



- Hf-STJ can achieves 2% energy resolution for $E\gamma \sim 25$meV because Δ_{Hf} is very small(0.02meV)

Expected energy resolution of Hf-STJ (F=0.2)



- Requirements for the COBAND experiment
  - Leakage current@20μV： 10pA@50mK(if signal width = 1μsec)

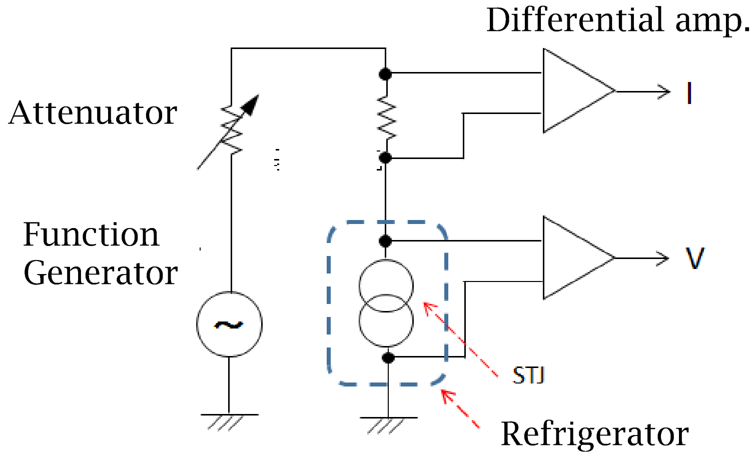
Development environment

Production:

- Hf-STJ is produced in a clean room at KEK
  - Thin-film formation using magnetron spatter
  - Patterning with photolithography process
  - Dry etching using ICP-RIE
  - Thermal oxidation

Measurement:

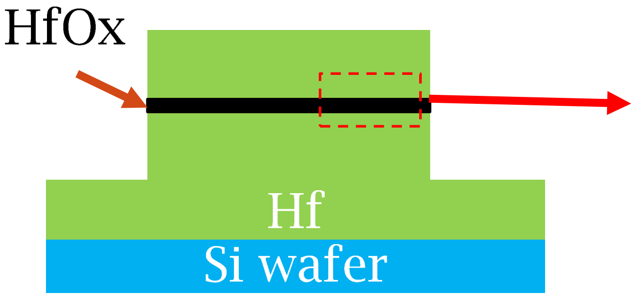
- T~120mK using a dilution refrigerator
- measure IV characteristic and light response by the 4 terminal method

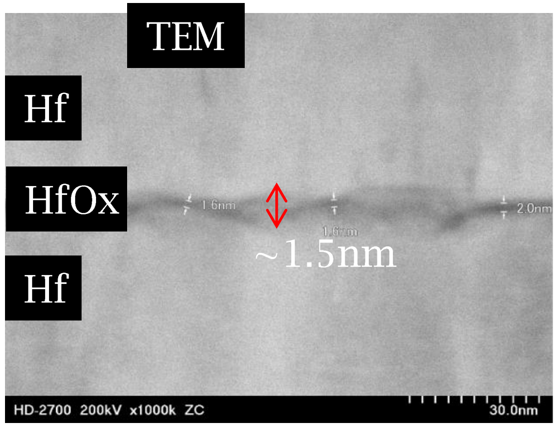


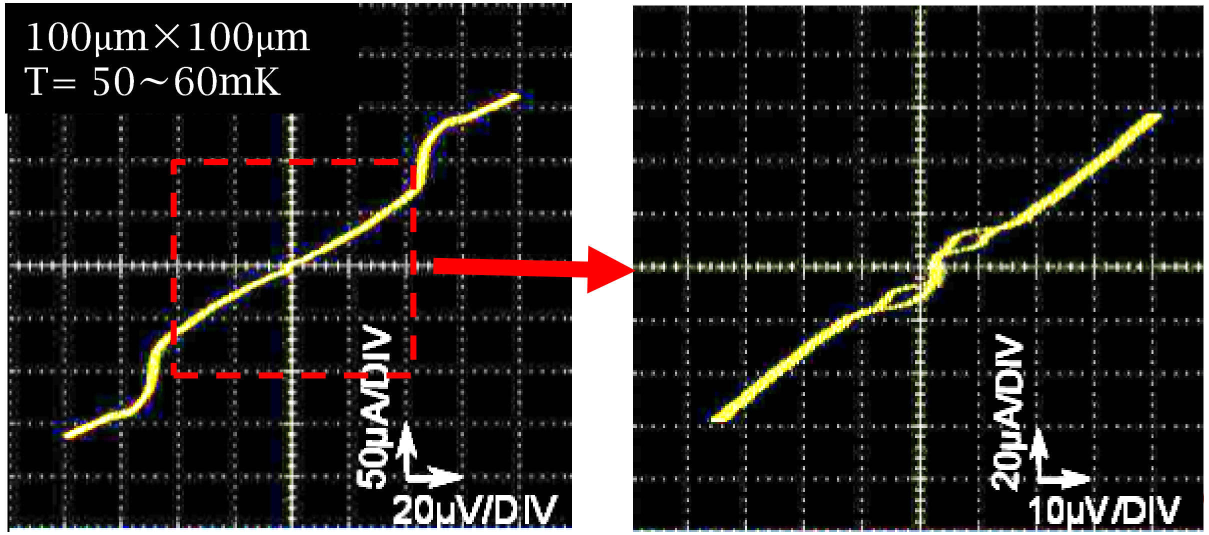
Development of Hf-STJ

- 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.

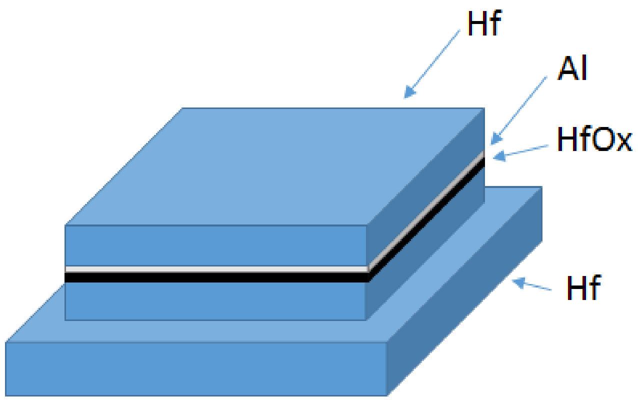


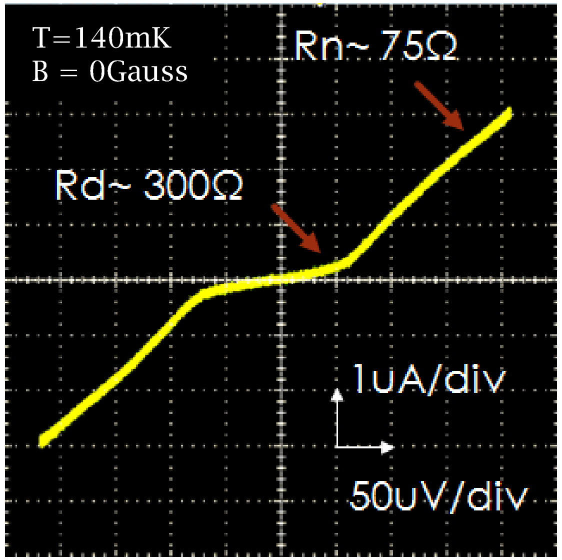




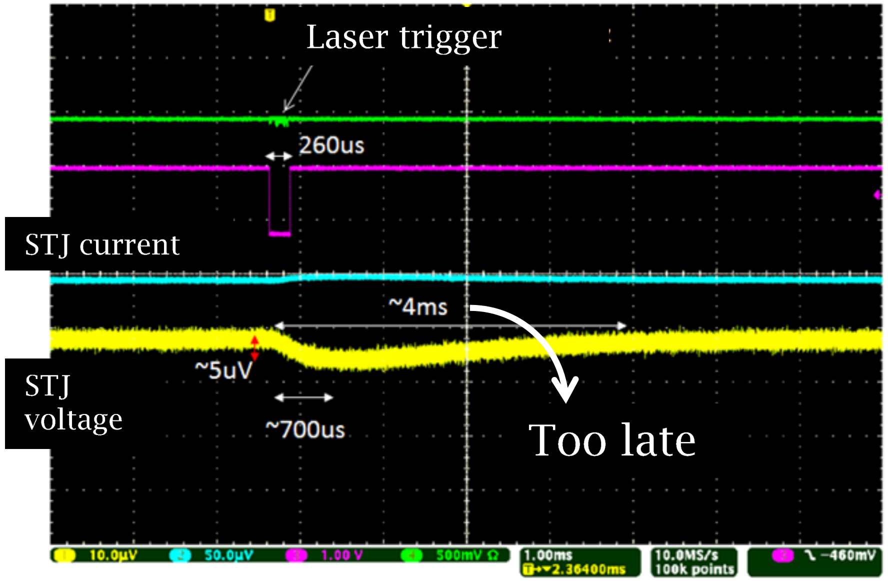
Development of Hf-STJ

- To reduce leakage current, we review the structure of Hf-STJ.
- We add thin (10nm) Al layer between the insulator and the upper Hf layer.
  - I_{leak} at 20μeV = 60nA@140mK (200μm × 200μm sample)
  - Josephson current wasn't observed.
  - Δ = 30~100μeV. ← proximity effect of Al
- I_{leak} was improved, but…
  - Tunnel probability is too small.
  - Δ is large. → worse energy resolution



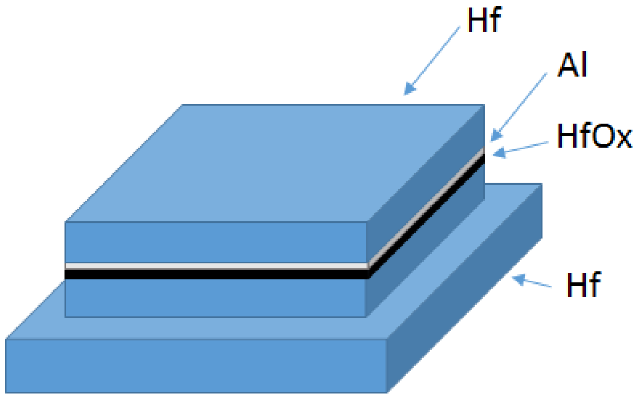


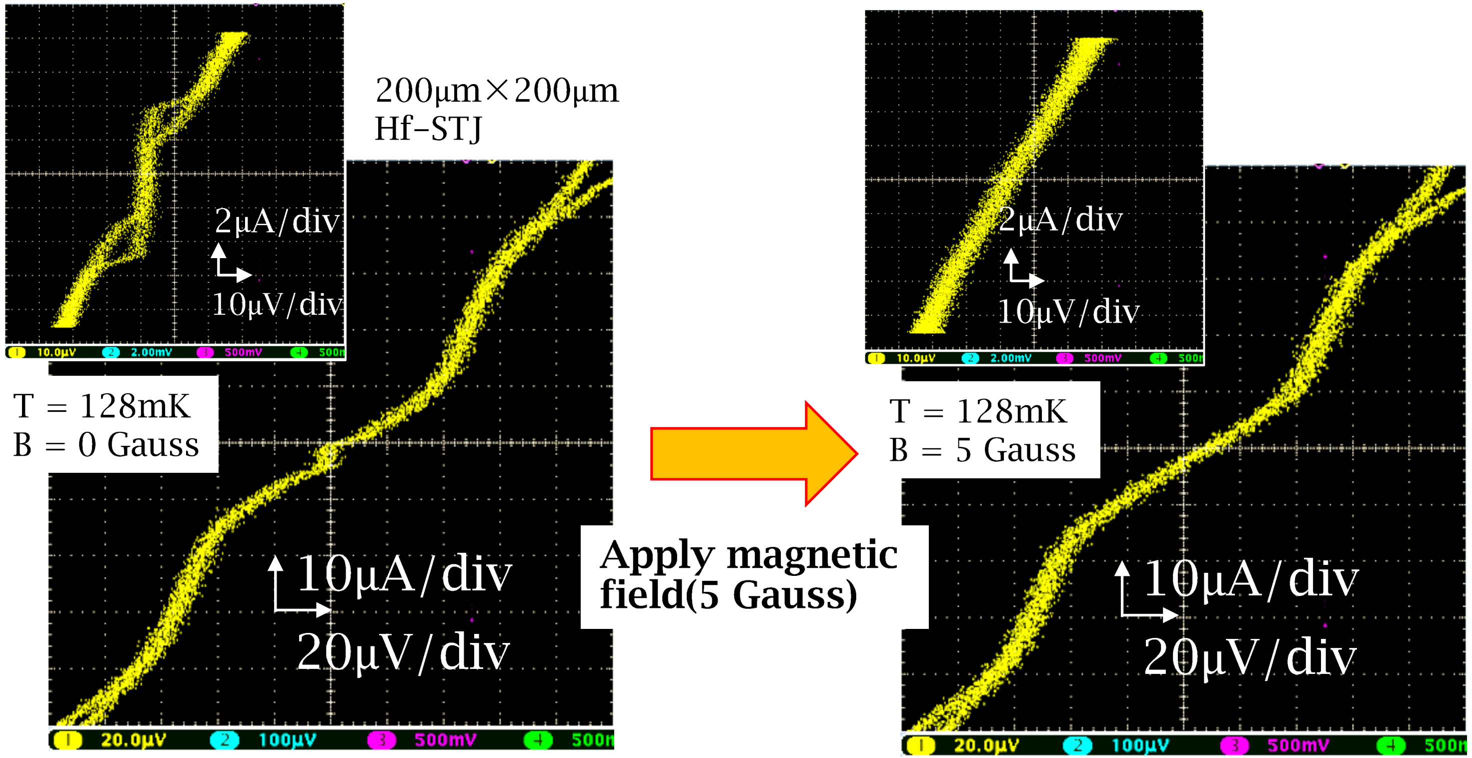
Response to visible light
λ=465um
10MHz oscillation 260μs per 1s



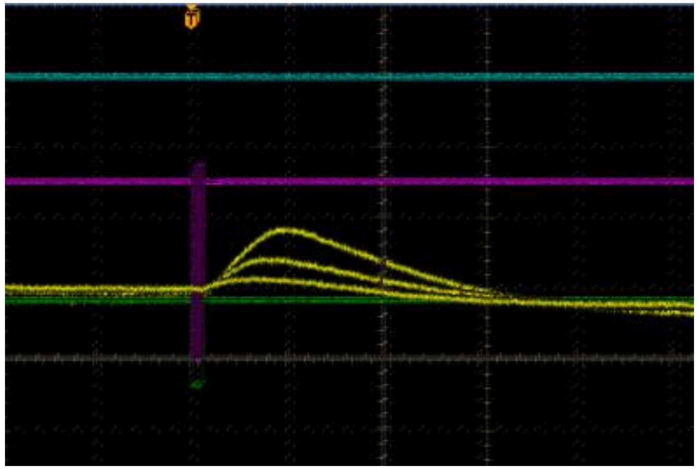
Development of Hf-STJ

- We made Al layer thinner.
  - Josephson current is observed and it's suppressed by magnetic field.
  - Δ = 20~25μeV (~Δ_{Hf})
  - 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)



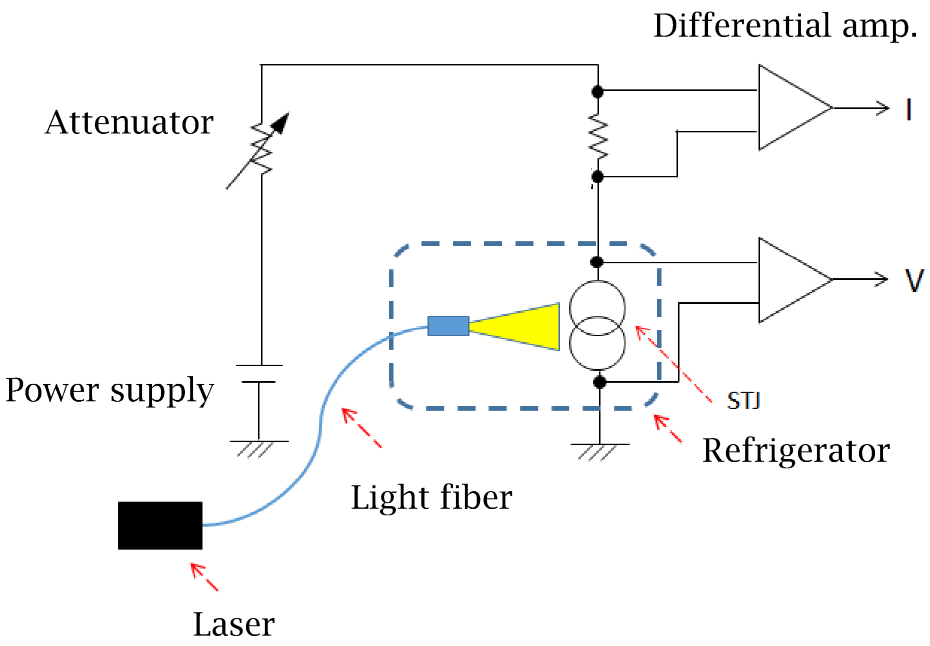


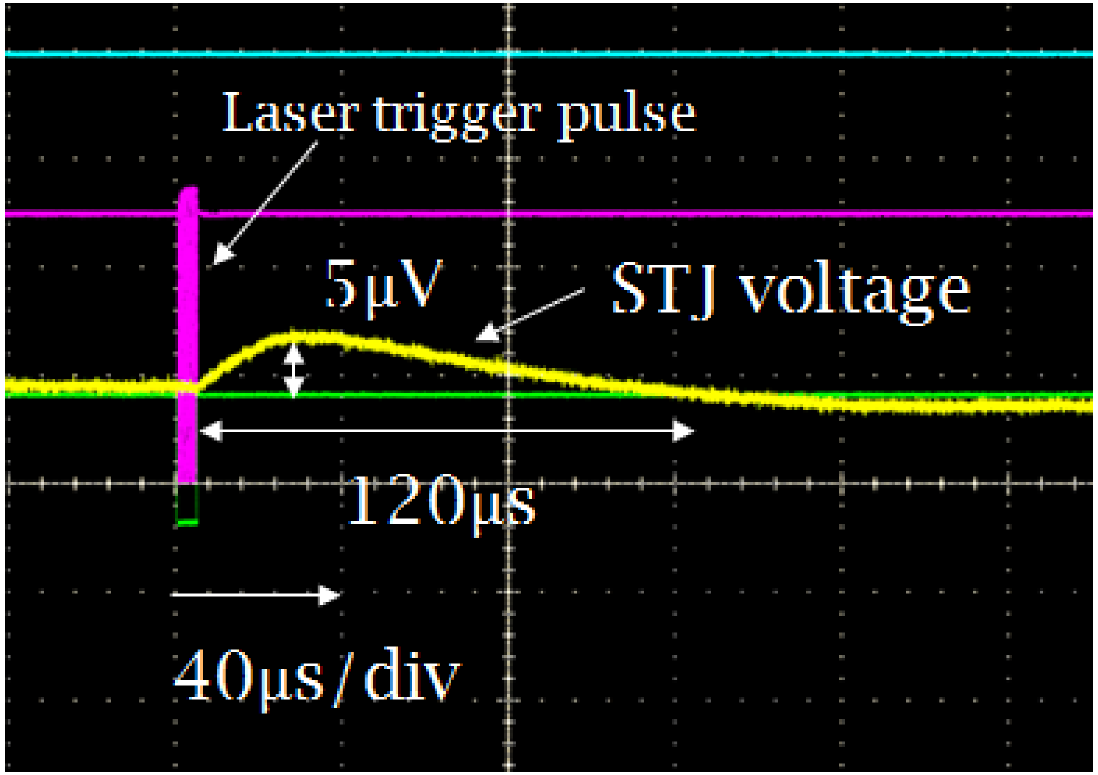
Response to visible light



Response to laser pulse

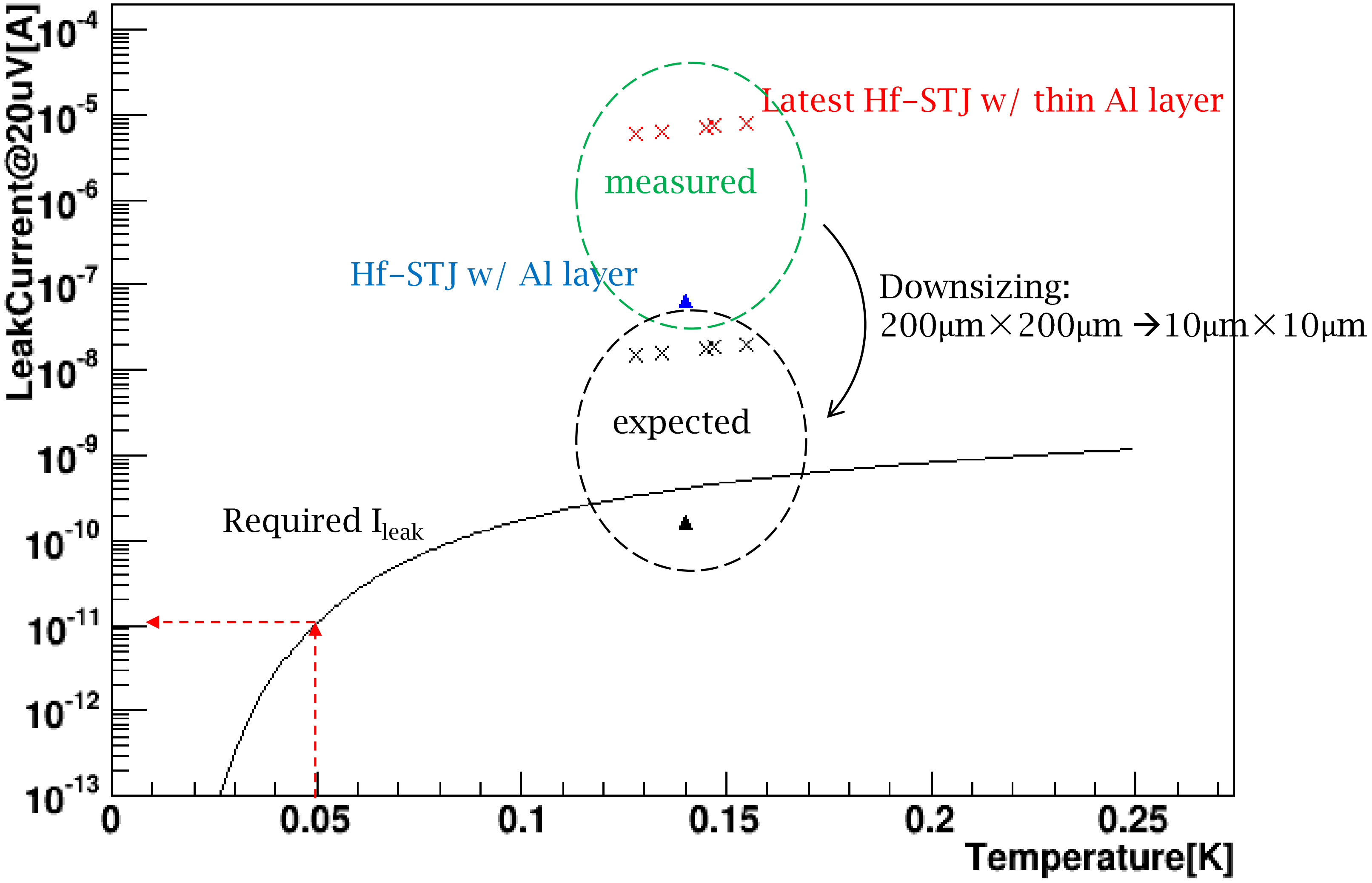
- 465nm laser
- 5MHz oscillation 5μs per 100ms.





Ideas for an improvement

- Downsizing
- Plasma oxidation
- Planarize the under Hf layer
- Etc…



Summary

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

- Leakage current of Hf-STJ is improved and Hf-STJ 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.
- Improvement is underway