R&D status of Hf-STJ

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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**.

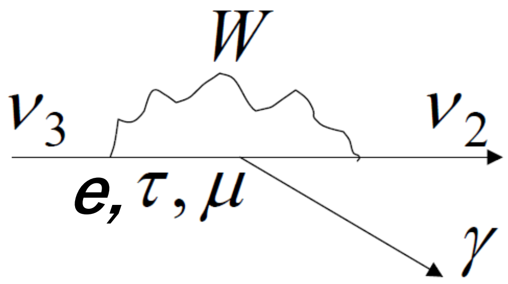
Neutrino decay is a radiative decay in which a lighter neutrino and a photon are emitted from a heavier neutrino.

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

Energy of the photon is given below

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

- → We can obtain neutrino mass itself.



Feynman diagram of neutrino decay

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

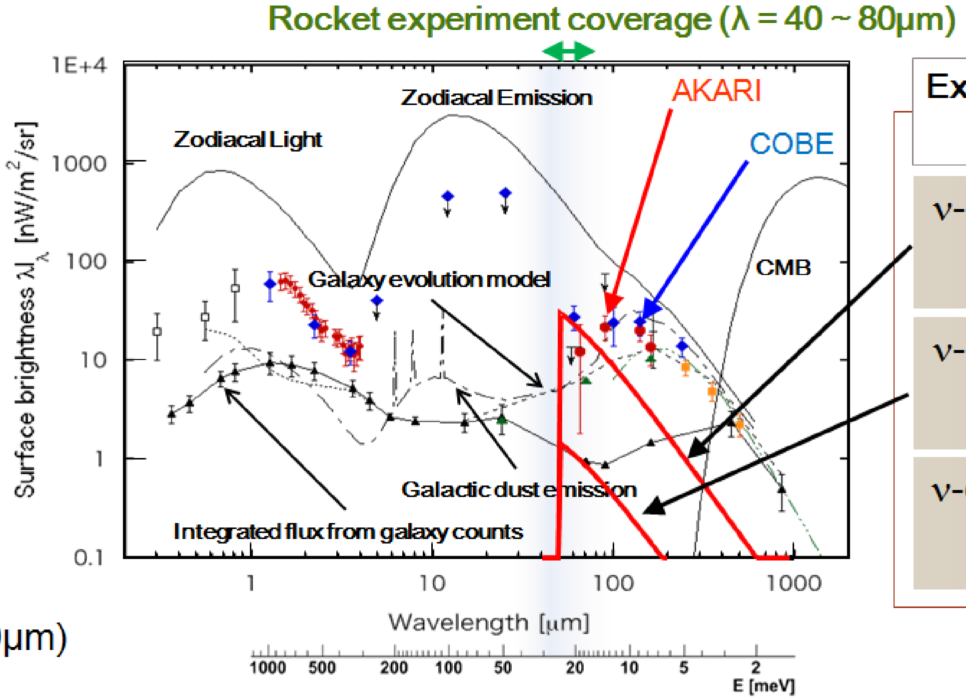
- Lifetime of neutrino is very long($\tau_3 > 10^{12}$year, J.Phys.Soc.Jpn.81,024101(2012)), to observe ν decay, we need an immense number of neutrino.
- Most promising method is to observe the decay of cosmic background neutrino(CBN).
  - CBN has a temperature of 1.9K and a particle density ρ of 110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

Background

Zodiacal Emission
λI_λ~500nW/m²/sr

CIB (COBE)
λI_λ~30nW/m²/s

at E_γ = 25meV (λ = 50μm)



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

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

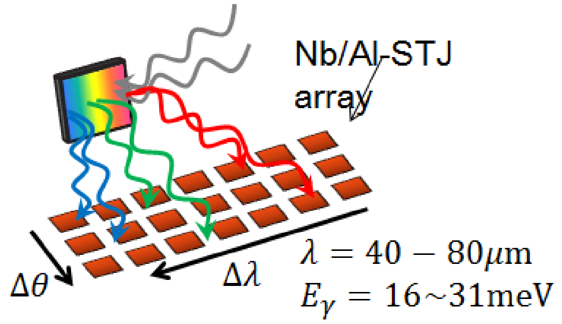
By measuring the energy spectrum of the Zodiacal Emission with the CBN decay continuously, we can see the CBN decay signal as a high energy cutoff.
To identify the shape edge, we need detector which has better than 2% resolution for E_γ ~ 25meV(λ~50μm)

The COBAND experiment

The COBAND experiment consists of two types of measurements:

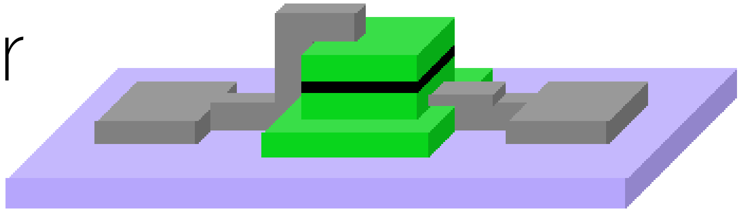
- **Rocket experiment**
  - 200sec data acquisition at 200km height in 2019.
  - Telescope: diameter:15cm, view angle: 0.006° ×0.05°
  - Improve the current limit of lifetime $\tau(\nu 3)$ by two orders of magnitude (~10^{14}years).
  - Detector: Array of 50 Nb/Al-STJ pixels with a diffraction grating covering $\boldsymbol{\lambda}$**=40－80**$\boldsymbol{\mu m}$

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

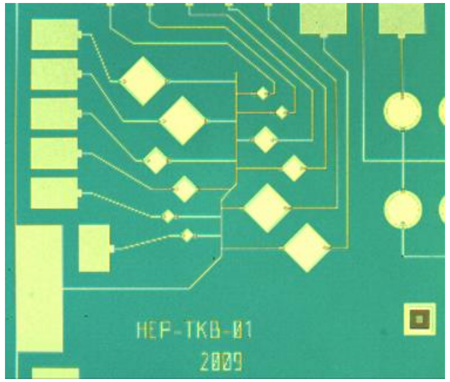


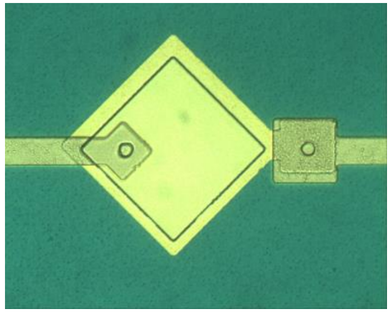
- **Satellite experiment after 2020**
  - 100days measurement at satellite
  - Telescope: diameter:20cm, view angle: 0.1°
  - Expected sensitivity: $\tau(\nu 3) \sim 10^{17}$year
  - Detector: **STJ detector using Hafnium**(**Hf-STJ**)

STJ (Superconducting Tunnel Junction) Detector



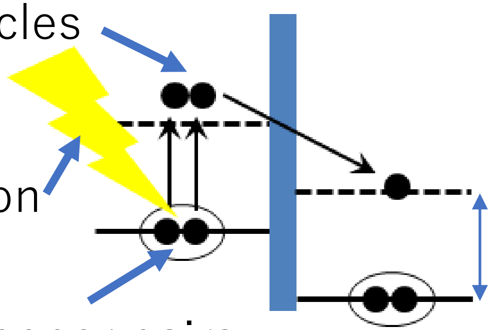
Overhead view of STJ detector



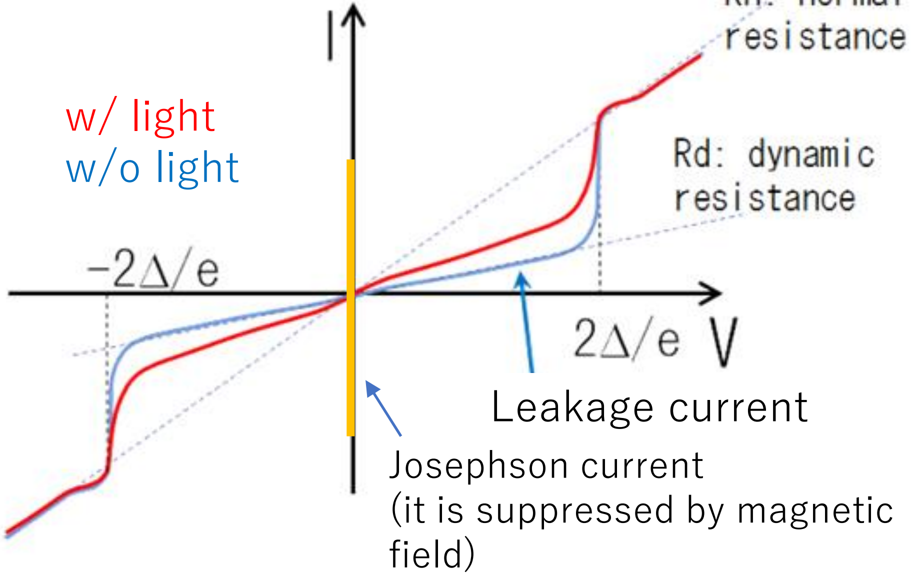


- **Structure**
  - STJ is a type of Josephson junction composed of Superconductor/Insulator/Superconductor
  - Size: dozens～hundreds μm square and 500 nm height

- **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.



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.

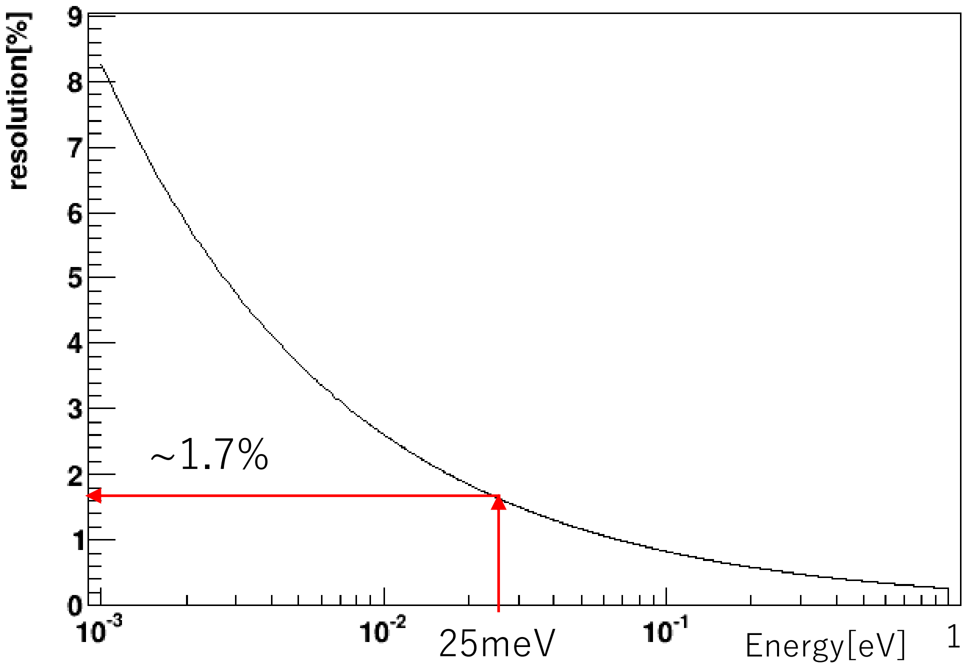
$$\sigma_E/E = \sqrt{(1.7\Delta)F/E}$$

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

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



- Hf-STJ as a photon detector is not established
- $N_{q.p.} = 25meV/1.7\Delta = 735$
- 2% energy resolution is achievable because Δ_{Hf} is very small.

→ We are developing Hf-STJ.

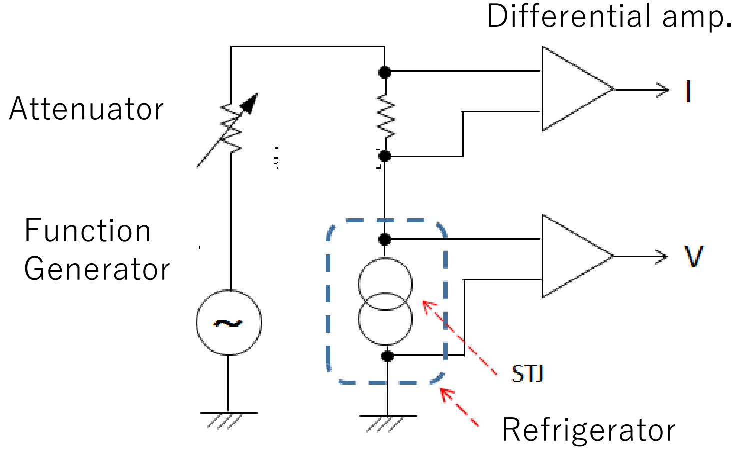
Development environment

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~140mK using a dilution refrigerator
- measure IV characteristic and light response by the 4 terminal method



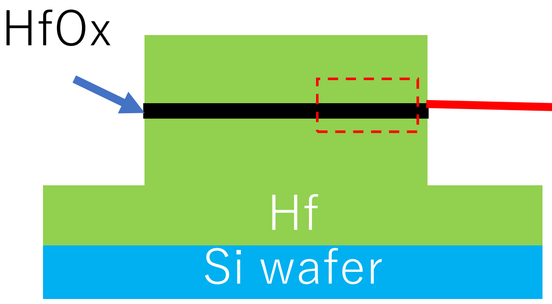
Earlier version of Hf-STJ

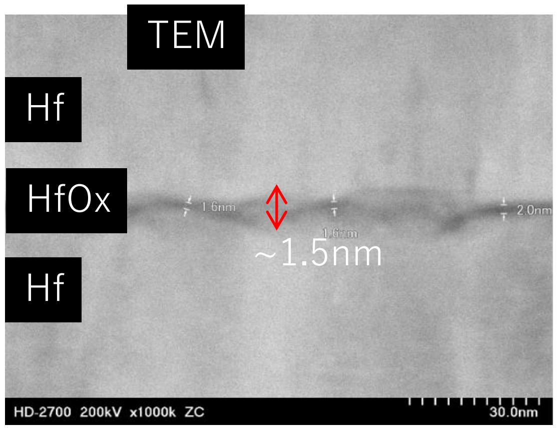
- Earlier version of our Hf-STJ
  - Structure: Hf/HfOx/Hf = 250nm/1.5nm/300nm
  - $\Delta \sim 20\,\mu$eV (= Δ of bulk Hf)
  - Leakage current ~ $20\,\mu$A@50mK, $20\,\mu$V ($100\,\mu$m × $100\,\mu$m sample)

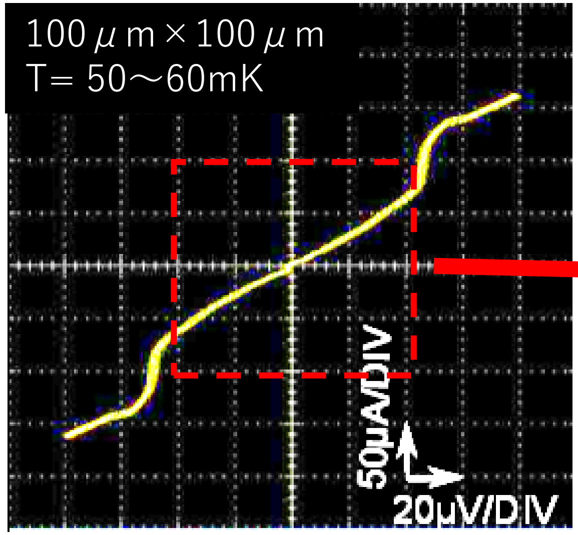
Leakage current is too large.

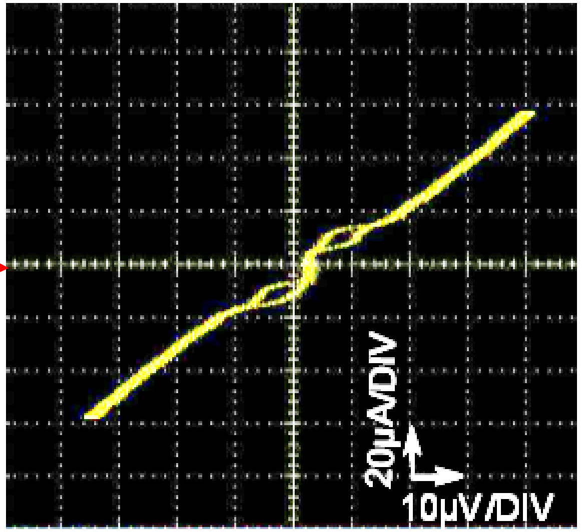
Required leakage current = 10pA@50mK

Necessary to perform improvements very much.



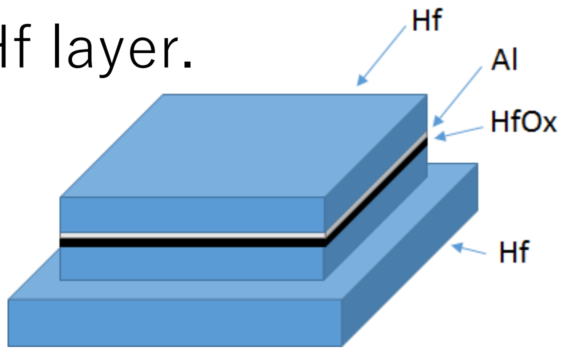


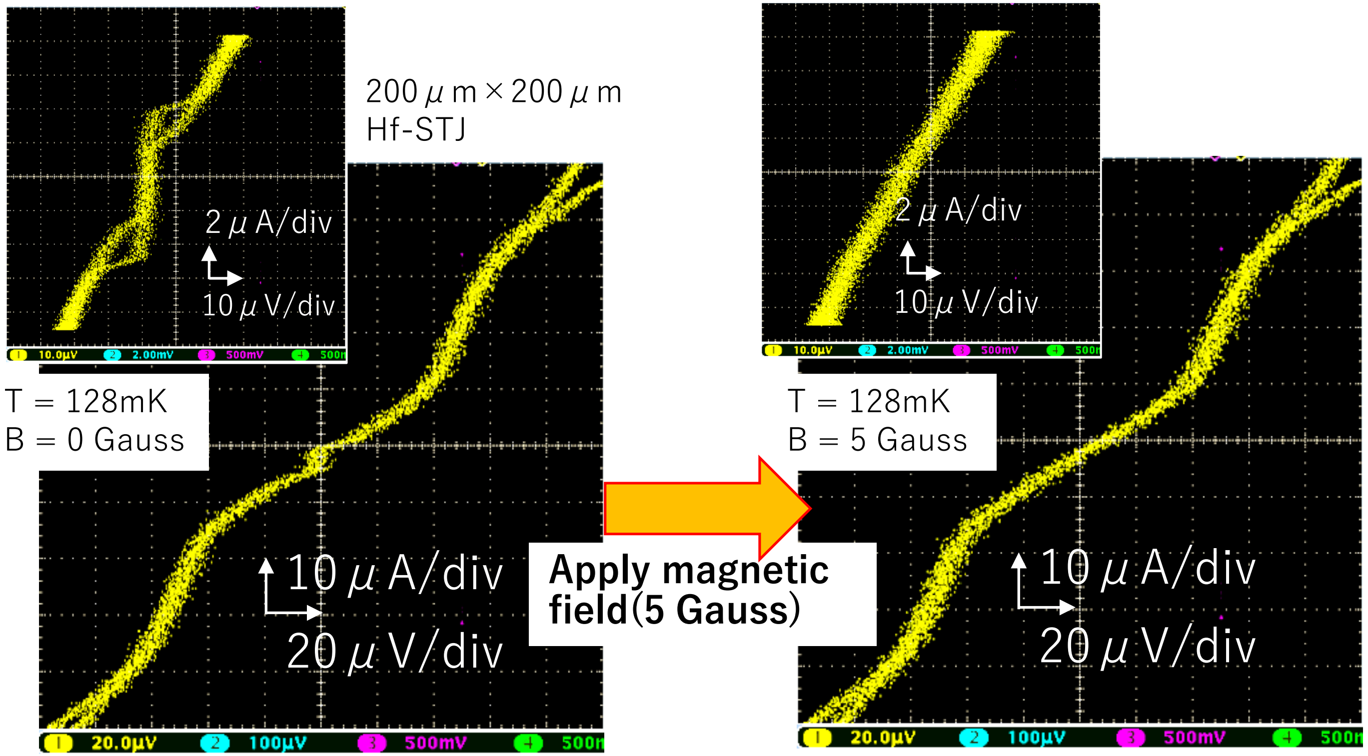


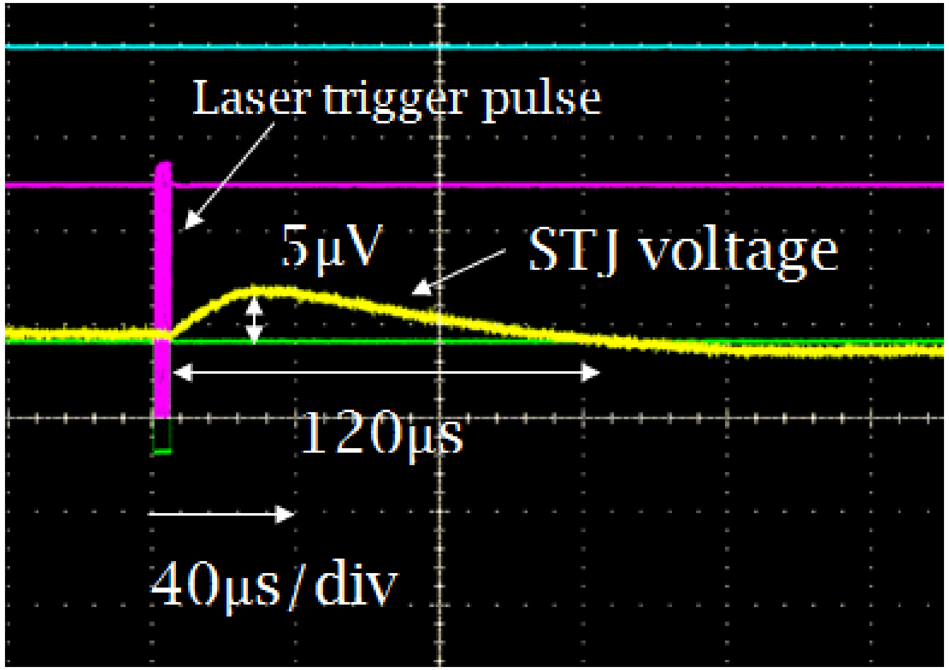


Earlier version of Hf-STJ (Hf-STJ w/ thin Al layaer)

- We made another type 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.
    - $\Delta = 20\sim30\,\mu\mathrm{eV}$.
    - I_{leak} = **5μA**@128mK (200μm × 200μm sample)
    - **Response to visible laser pulses is observed.**
    - But leakage current is still large. Need more improvement.







Response to laser pulses

- λ=465nm

Improvements

- Our Hf-STJ works as STJ photon detector.
- But leakage current is very large, need more improvement.

Ideas for improvement are as follows

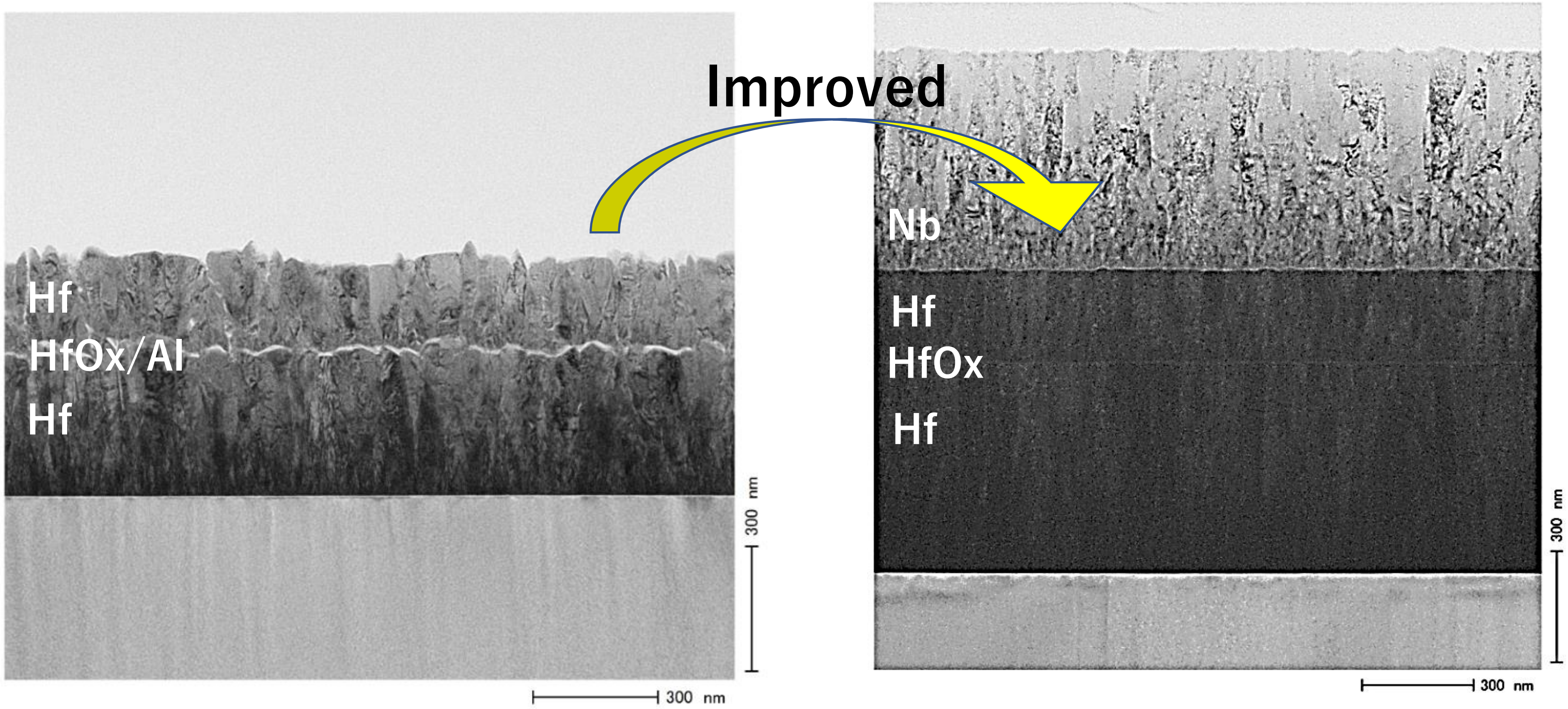
- Improvement of surface roughness of Hf layer
  - Rough surfaces of Hf layer cause defects of insulators.
  - We modified the sputtering condition to make smooth Hf layers.
- Downsizing
  - Leakage current tends to fall in inverse proportion to junction size.

Improvement of Hf surface roughness

- We performed sputtering parameter search, then surface roughness improved.

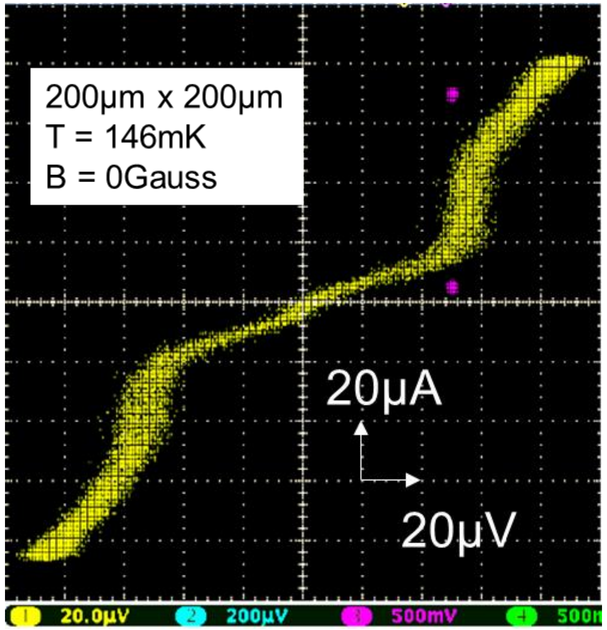
Old sputtering condition
Ar 2.0Pa, 80W

New sputtering condition
Ar 0.5Pa, 50W

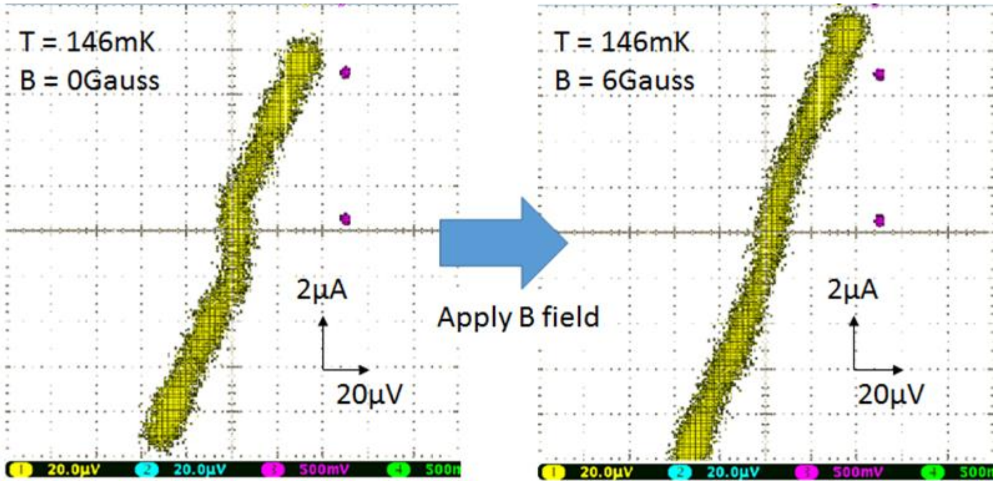


Hf-STJ using smooth Hf (200um sq.)

- Josephson current is observed (~2μA).
- Δ~25μeV.
- Leakage current: 7μA@20μV.
  - I_{leak} becomes 3 times smaller than old sample.
- Response to visible light is observed. 7μA increase by light illumination.

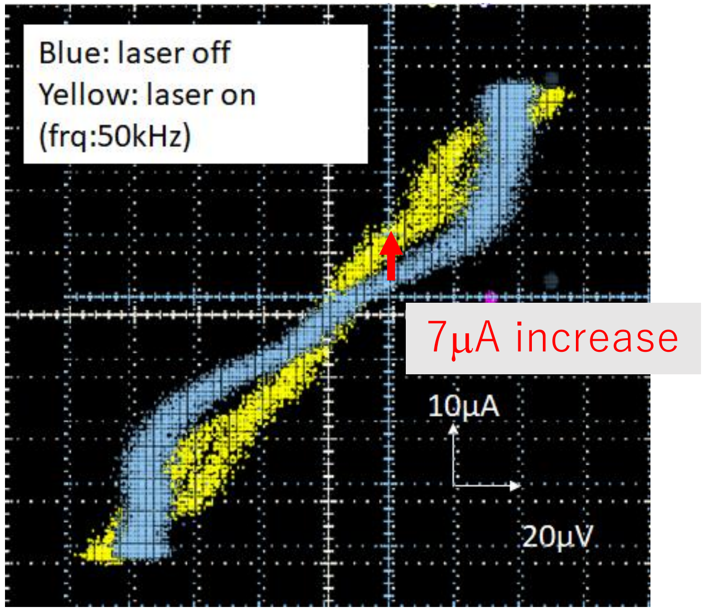


IV characteristic



IV characteristic (near 0V, B=0Gauss)

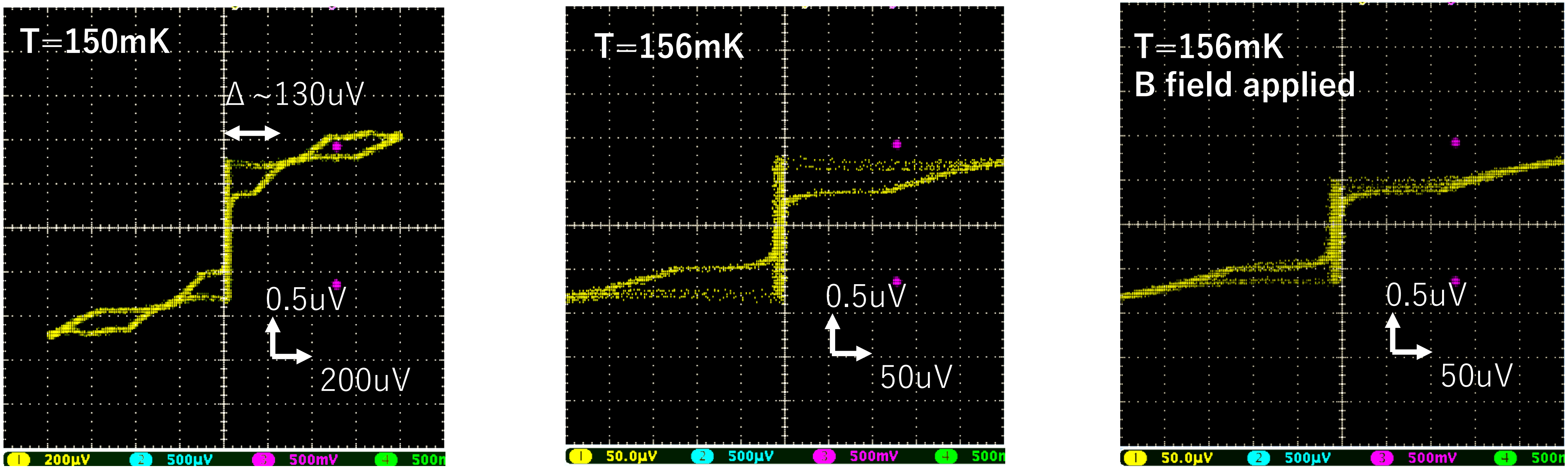
IV characteristic (near 0V, 6Gauss)



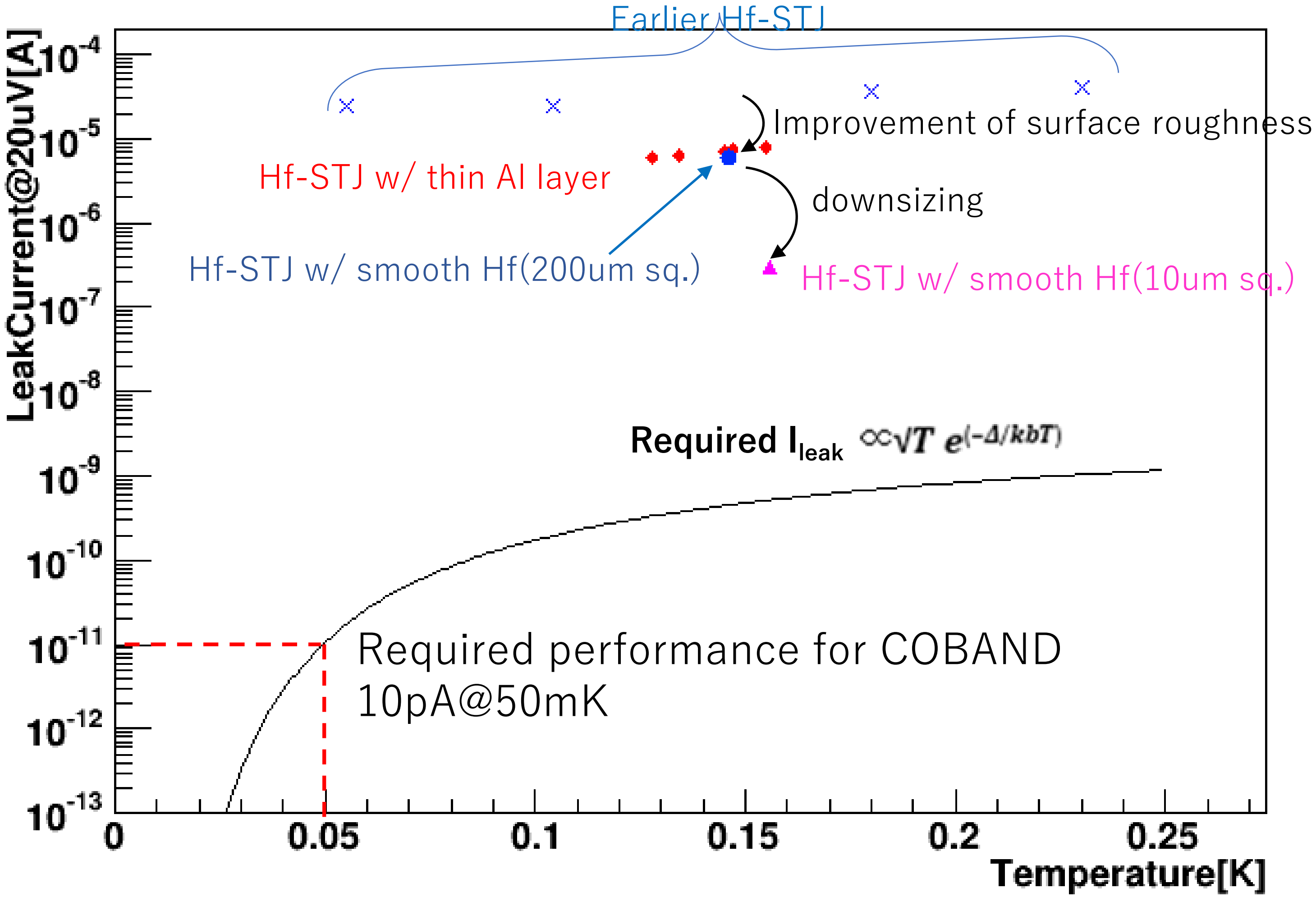
Response to visible(λ=465nm) DC-like laser light
T = 140mK, 9Gauss B field is applied.

Hf-STJ using smooth Hf (10um sq.)

- Josephson current is observed (~0.7 μA)
- Δ~130 μeV.
- Leakage current: 0.3 μA@20 μV
  - I_{leak} becomes 23 times smaller than 200um sq. sample.



- Leakage current is reduced by improvement of roughness of Hf layer and downsizing
- However, leakage current is still large, need more improvement.



- Also, we need to measure characteristics of STJ at more low temperature.
- Our dilution refrigerator is out of condition.
  - achieving temperature is ~140mK
  - We are fixing it. but it is proceeding with difficultly.
- Therefore, we have not measured characteristics of Hf-STJ with sufficient cooling.

What we want to do at KAIST

- We would like to use a dilution refrigerator to measure characteristics of Hf-STJ with sufficient cooling.

- 1st step
  - Measure IV characteristics at 100mK or lower.
    - Sample size: 3cm x 3cm x 5mm
    - # of read out wire: at least 4
  - If possible, install a solenoidal coil to apply magnetic field to STJ.
- 2nd step
  - Observe response to the light illumination.
    - Install a optical fiber and solenoidal coil.