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R&D status of Hf-STJ for COBAND

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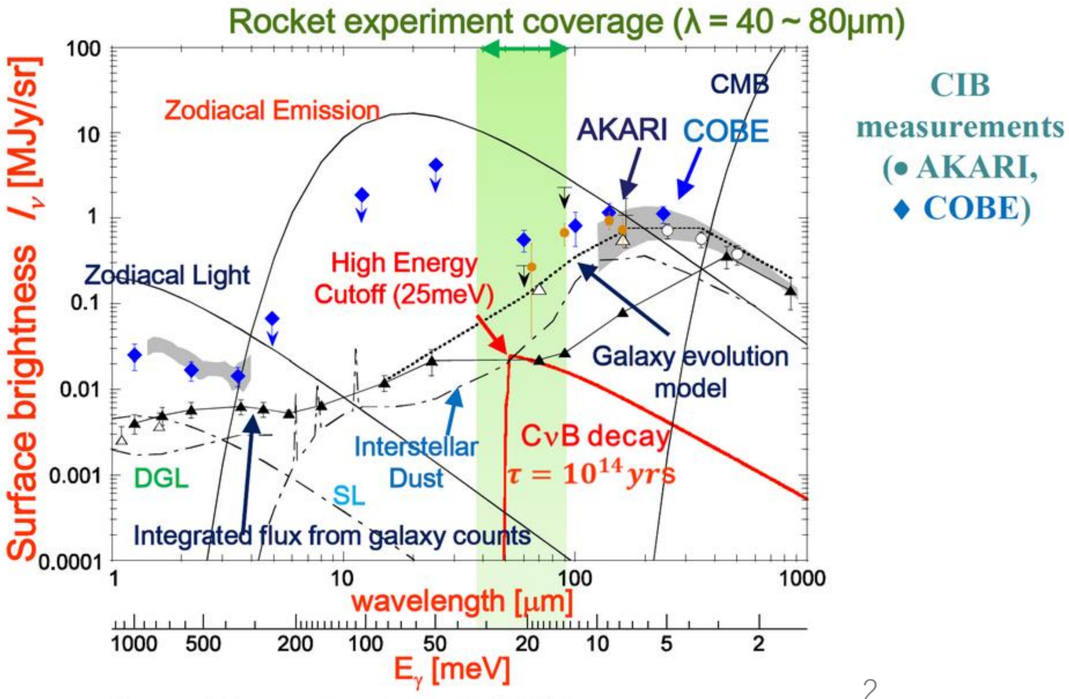
Introduction

- We are developing STJ detectors and cryogenic amplifiers for COBAND (COsmic BAckground Neutrino Decay search) experiment.

- Brief introduction of COBAND experiment
  - measure the neutrino mass by observing the neutrino decay of cosmic background neutrino.
  - COBAND experiment consists of two type of measurement: rocket experiment and satellite experiment

- Requirements for the detector
  - Continuous spectrum of photon energy around E=25 meV (λ=50μm)
  - Energy measurement for a single photon with a better than 2% resolution for E=25meV to identify the sharp edge in the spectrum

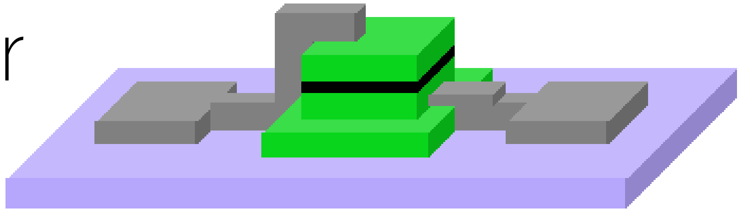
STJ can achieves requirements.
Nb/Al-STJ for the rocket experiment.
Hf-STJ for the satellite experiment.



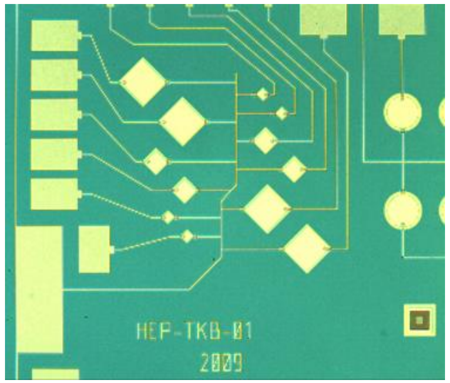
Source: S. Matsuura Astrophys. J. 737 (2011) 2

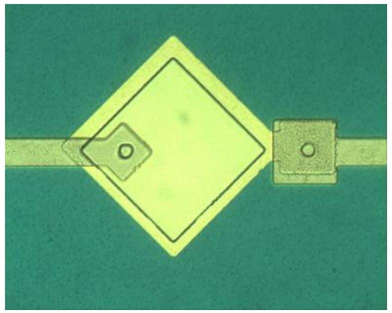
STJ (Superconducting Tunnel Junction) Detector

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



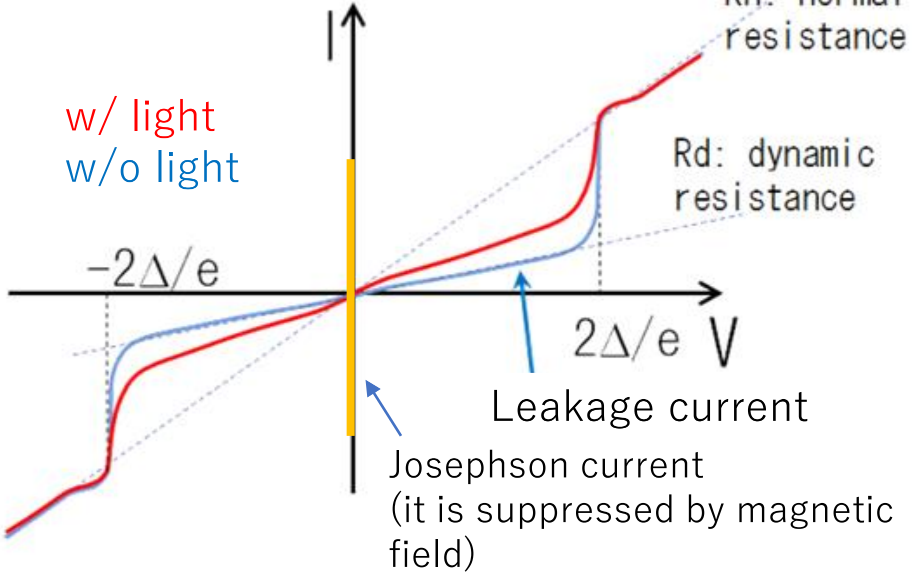
Overhead view of STJ detector

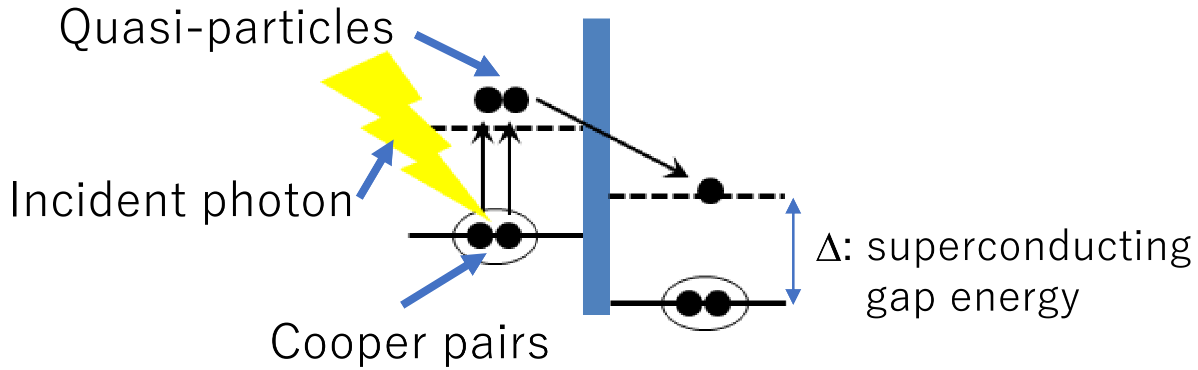




- **Working principle**
  - Incident photon is absorbed in the superconductor and excites cooper pairs.
  - Excited cooper pairs become quasi-particles.
  - Quasi-particles go through insulator by tunnel effect.
  - Number of quasi-particles is determined by energy of incident particle.
  - Thus, we 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.

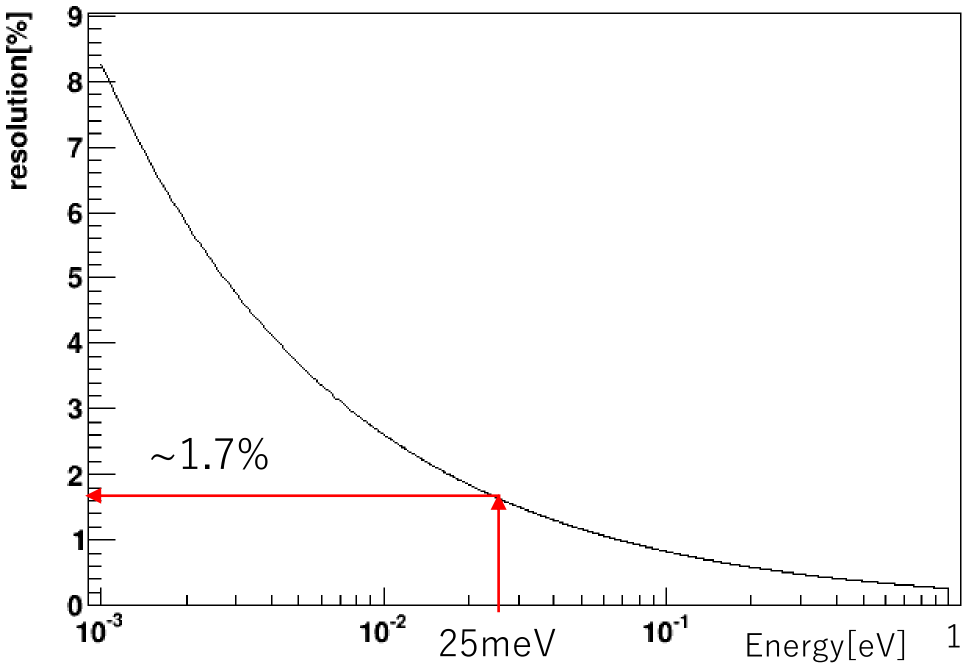
$$\sigma_E/E = \sqrt{(1.7\Delta)F/E}$$

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

Material	Tc(K)	Δ(meV)
Niobium	9.20	1.550
Aluminum	1.14	0.172
Hafnium	0.16	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.

Why Hafnium

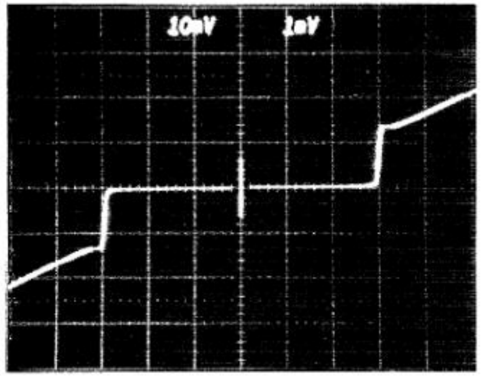
- COBAND satellite experiment requires photon detector which has 2% energy resolution at Eγ ~ 25meV.
- Metals whose **Δ < 0.029meV** can achieve required energy resolution.
  - $\sigma_E = \sqrt{(1.7\Delta)F\varepsilon}$
- To reduce thermal leakage current, STJ detector should be operated at T < 0.1Tc
  - **Metal which has bigger Tc is easy to use.**
  - But, Tc bear a proportionate relationship to Δ.
    - $2\Delta = 3.5k_BT_c$ (BSC theory)

Hf has highest Tc among metals which has Δ<0.029meV.

Material	Tc[K]	Δ [meV]
Nb	9.29	1.55
Pb	7.2	1.365
Ta	4.48	0.7
Sn	3.7	0.575
Al	1.18	0.172
Ti	0.39	0.058813
Hf	0.165	0.021
Ir	0.099	0.01493
Be	0.023	0.003468
W	0.016	0.0025
Rh	0.002	0.000302

Δ<0.29meV

Also, there is a report that HfOx works as insulator of STJ.



← Nb/HfOx-Hf/Nb STJ (200μm x 200 μm)
Sructure: Nb/HfOx/Hf/Nb = 200nm/?/3nm/200nm

High-quality Nb/HfOx-Hf/Nb Josephson junction, Appl.Phys. Lett, Vol.60, No.24, 15 June 1992, S.Morohashi et.al.

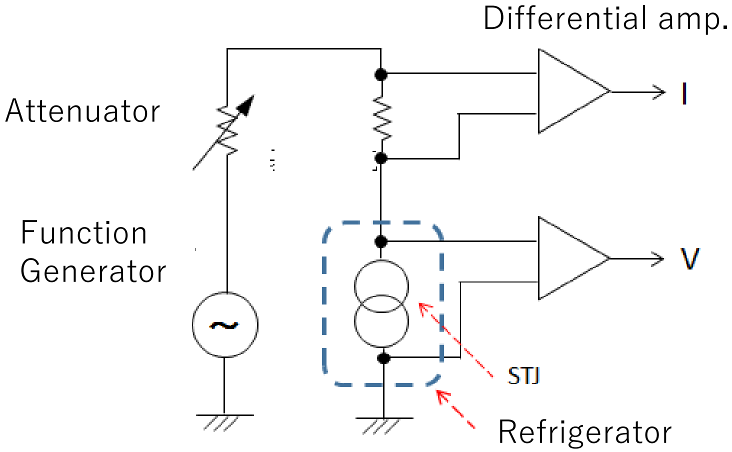
Development environment

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 (HfOx)

Measurement:

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



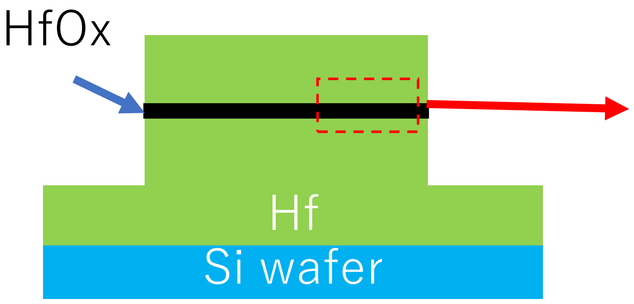
Earlier version of Hf-STJ

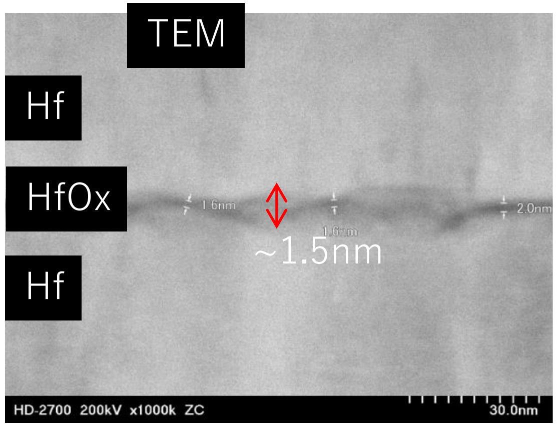
- Earlier version of our Hf-STJ
  - Structure: Hf/HfOx/Hf = 250nm/1.5nm/300nm
  - Δ ~ 20 μeV (= Δ of bulk Hf)
  - Leakage current ~ 20 μA@50mK, 20 μV (100 μm × 100 μm sample)

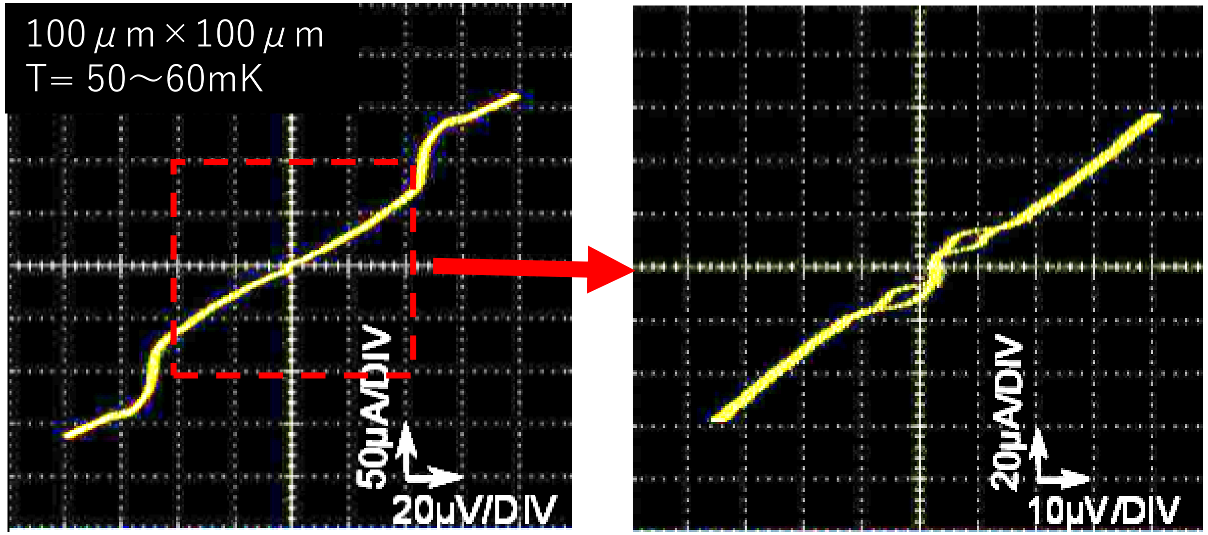
Leakage current is too large.

Required leakage current = 10pA@50mK

Necessary to perform improvements very much.

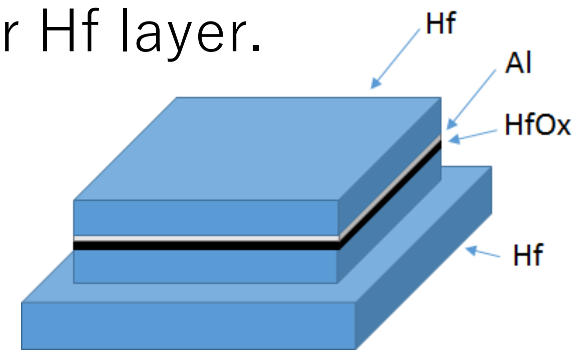


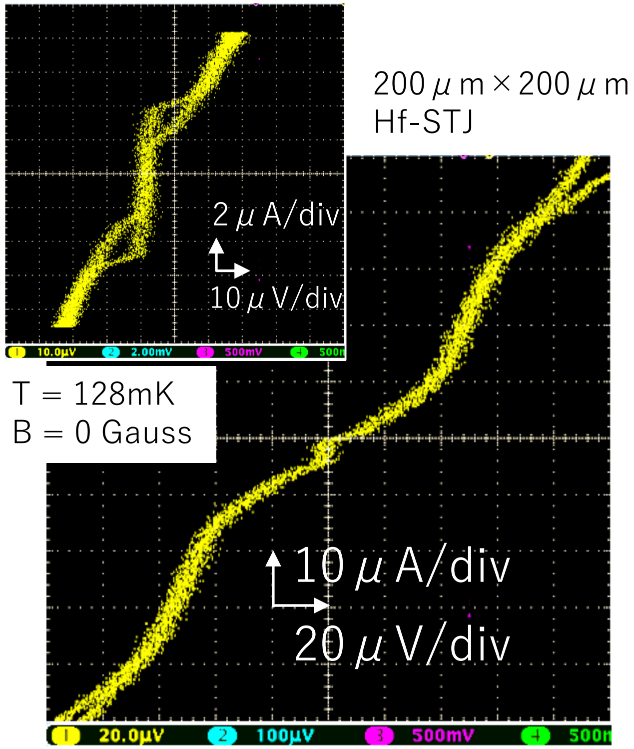




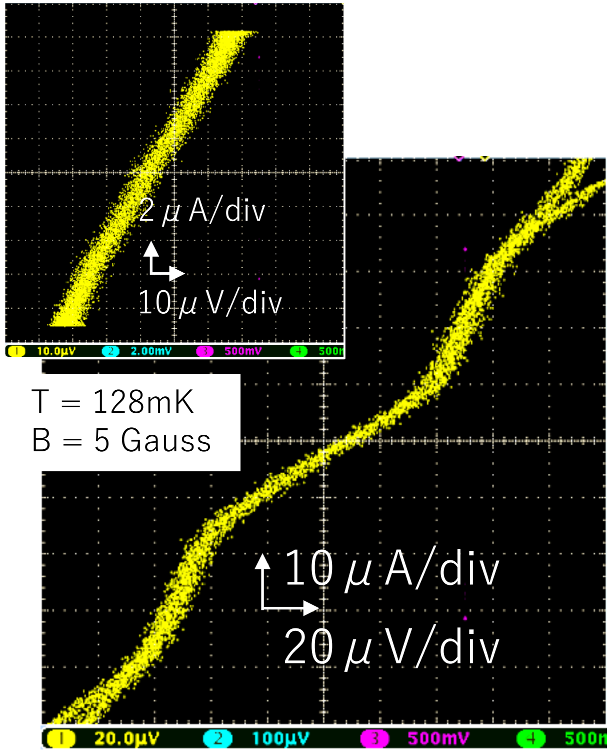
Earlier version of Hf-STJ (Hf-STJ w/ thin Al layaer)

- 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)



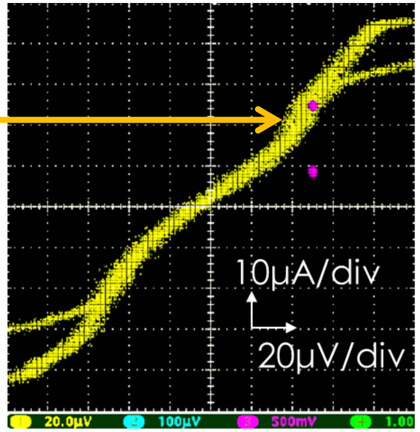


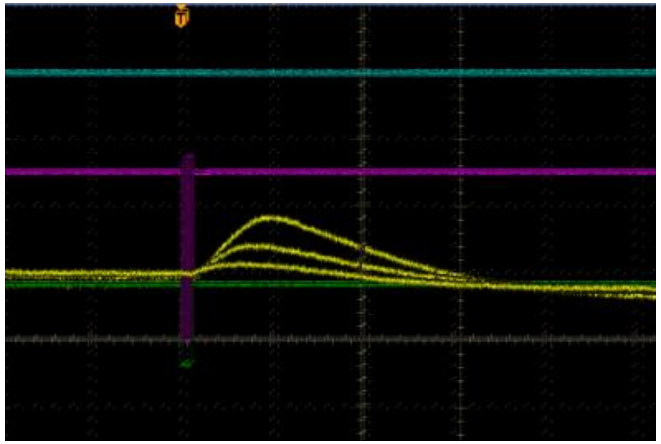
Apply magnetic field(5 Gauss)



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

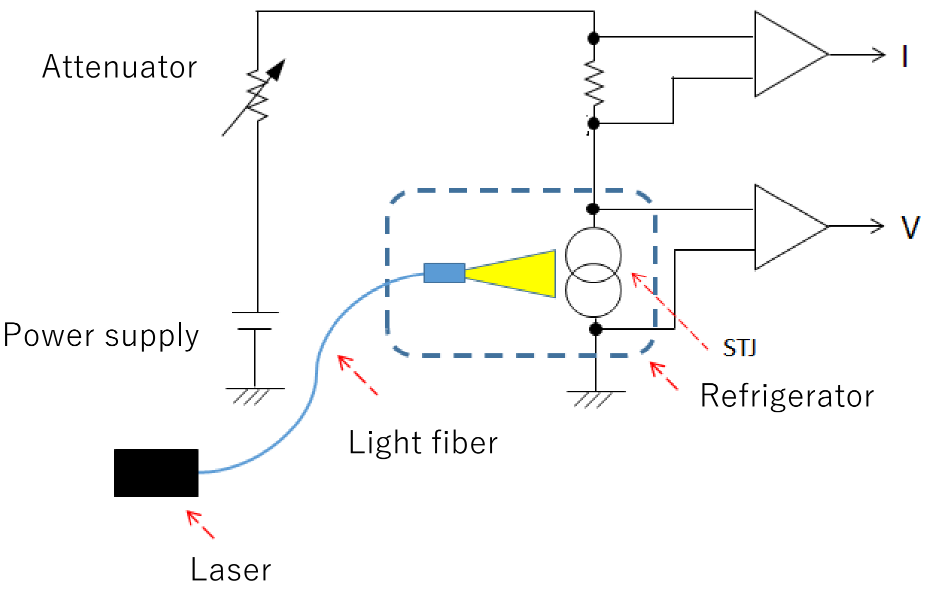
Operation point
20uA constant current

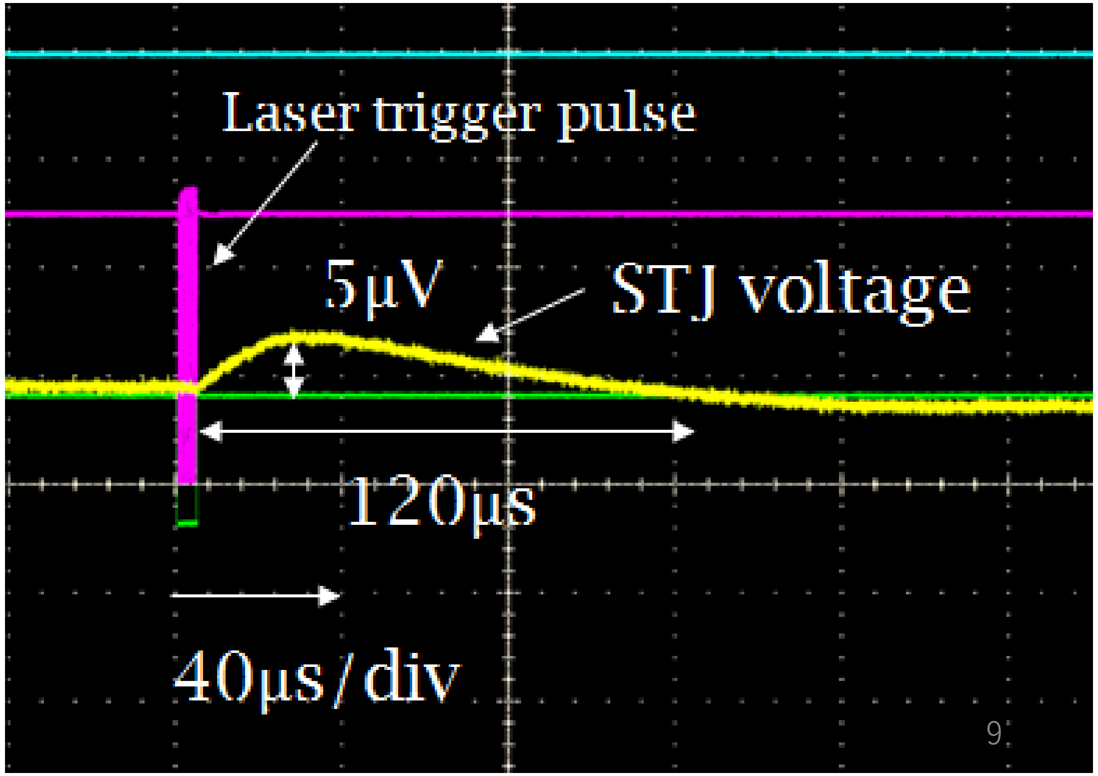




Response to laser pulse

- λ = 465nm visible laser
- 25 times oscillation during 5 us





Response to visible laser pulses is observed.

Improvements

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

Ideas for improvement are as follows

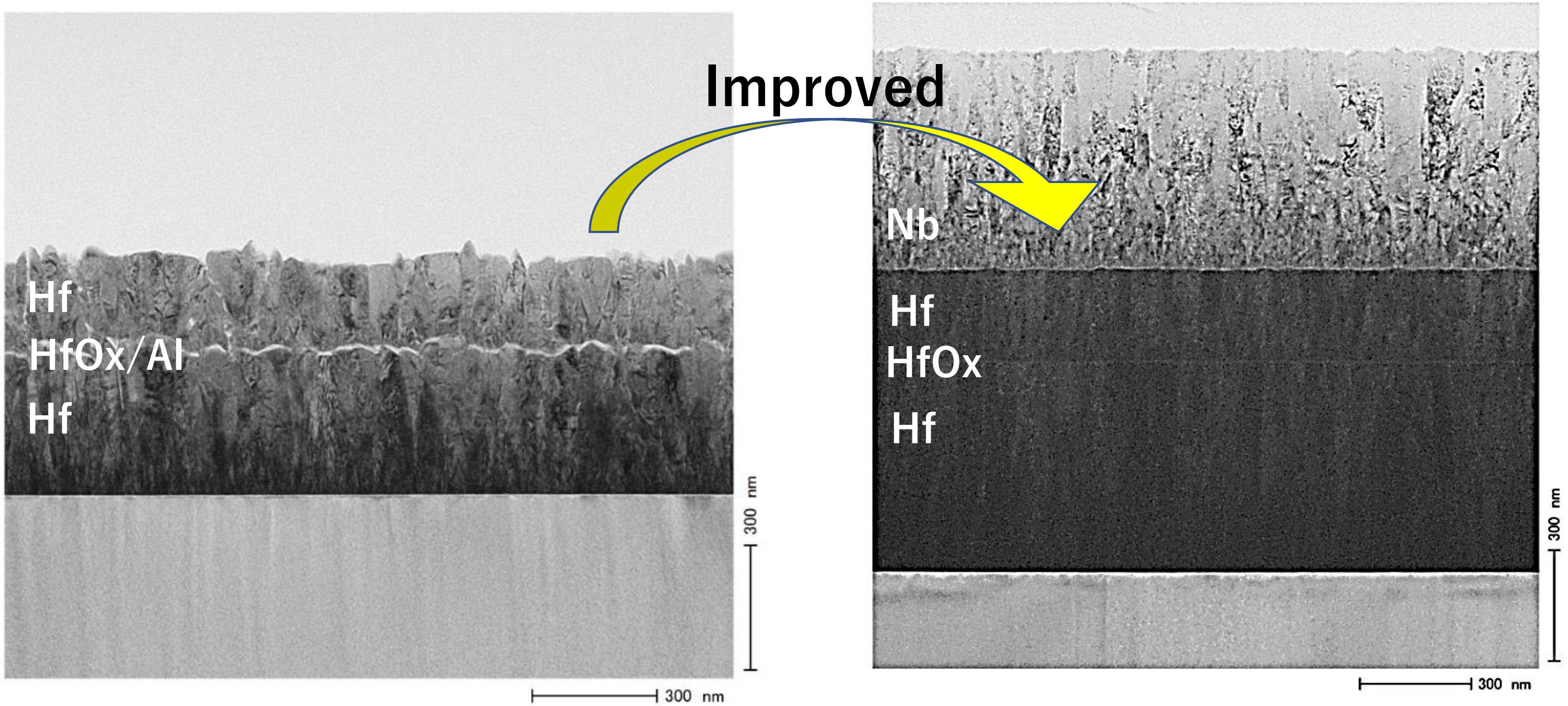
- Improvement of surface roughness of Hf layer
    - Rough surfaces of Hf layer cause defects of insulators.
    - We modified the sputtering condition to make smooth Hf layers.
- Decreasing junction size
    - Leakage current tends to fall in inverse proportion to junction size.

Improvement of Hf surface roughness

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

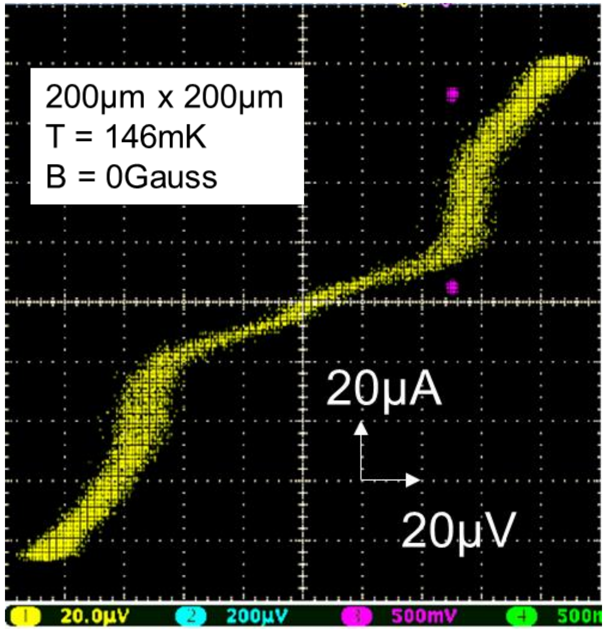
Old sputtering condition
Ar 2.0Pa, 80W

New sputtering condition
Ar 0.5Pa, 50W

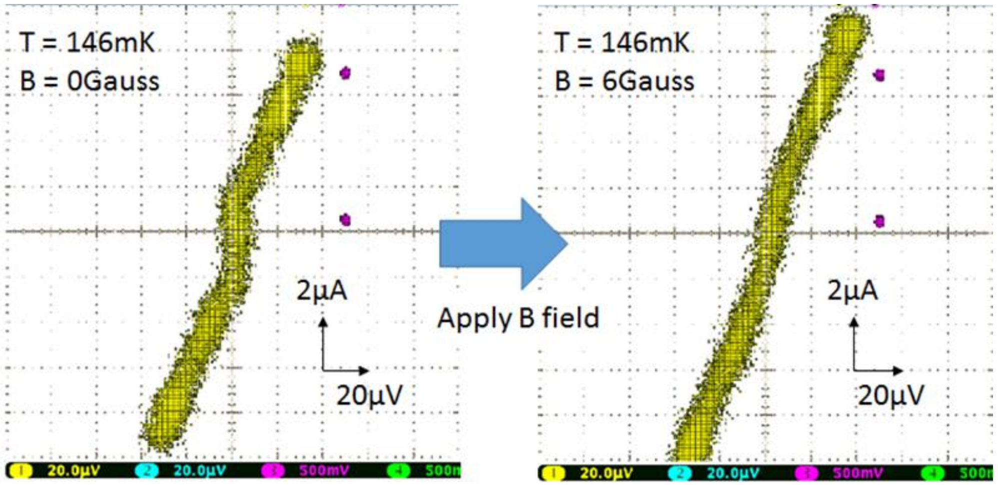


Hf-STJ using smooth Hf (200um sq.)

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



IV characteristic



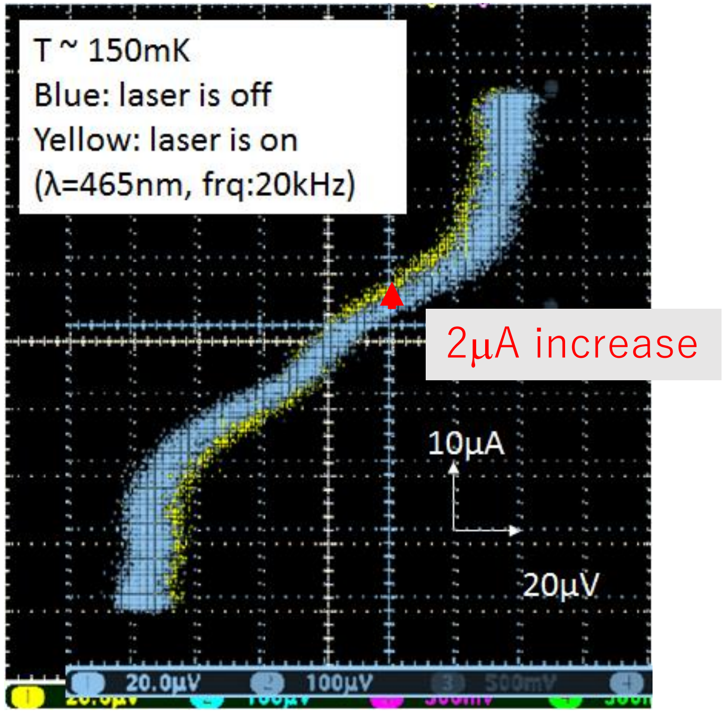
IV characteristic (near 0V, B=0Gauss)

IV characteristic (near 0V, 6Gauss)

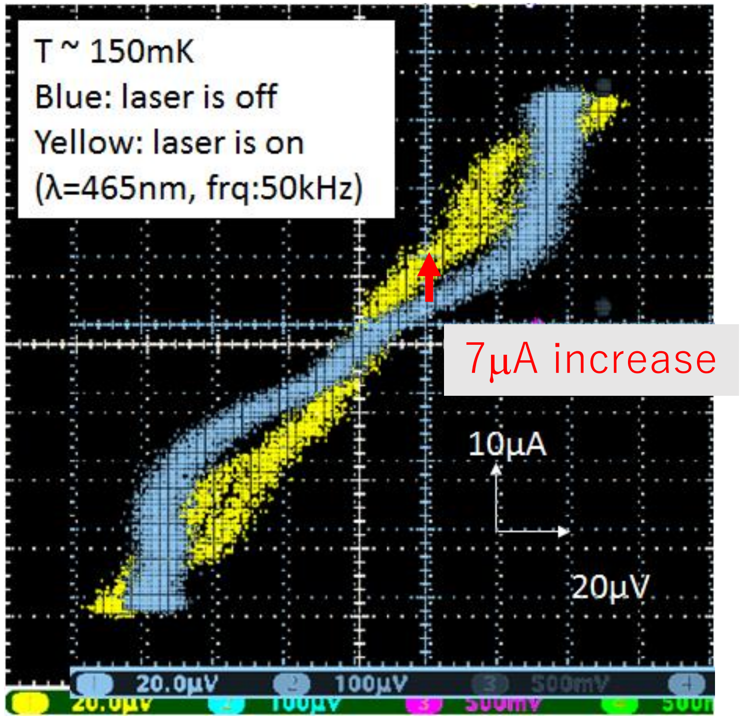
Hf-STJ using smooth Hf (200um sq.)

- Response to DC-like laser light (λ=465nm).
  - T=150mK
  - 9Gauss B field is applied

- 465nm laser, **20kHz oscillation**
- Current increase ~2 μ A @20 μ V by irradiation light.



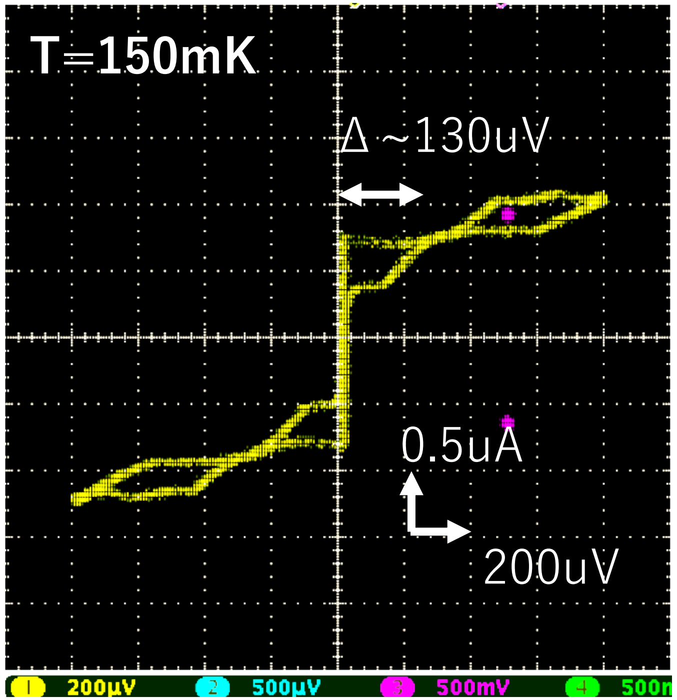
- 465nm laser, **50kHz oscillation**
- Current increase ~7 μ A @20 μ V by irradiation light.

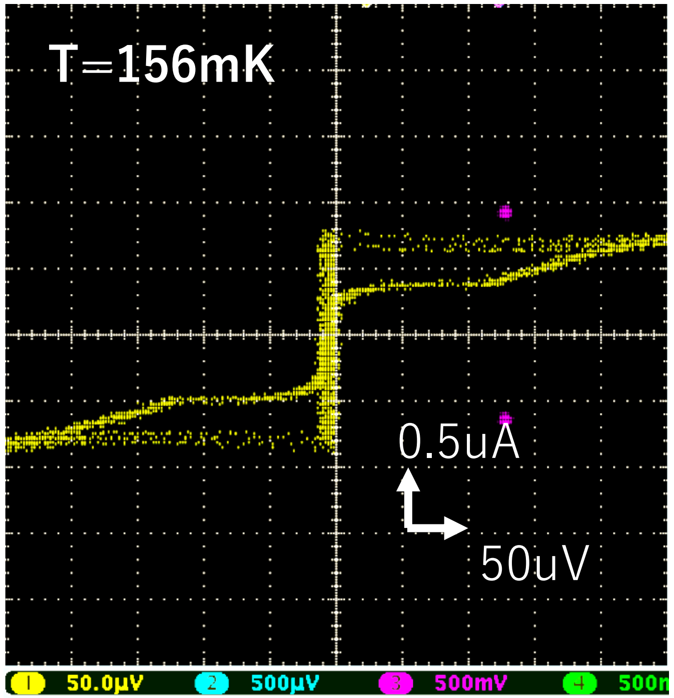


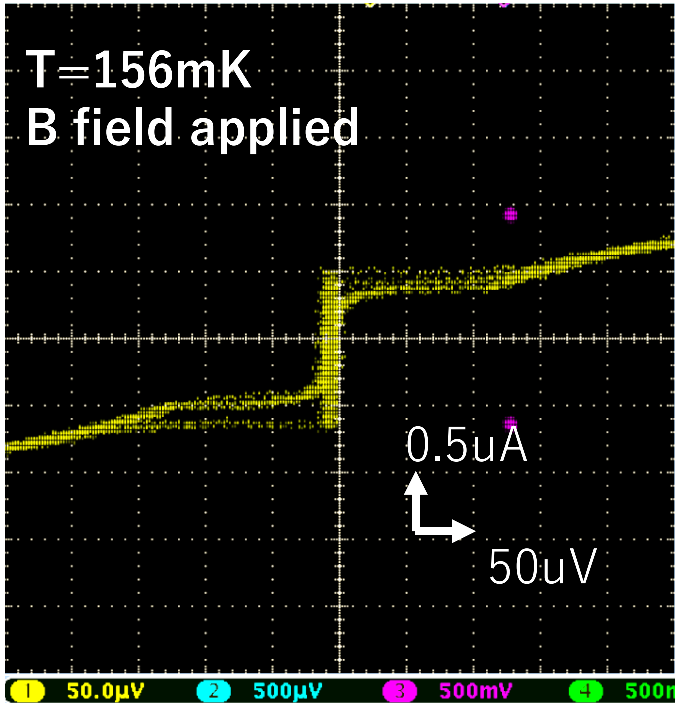
Hf-STJ using smooth Hf (10um sq.)

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

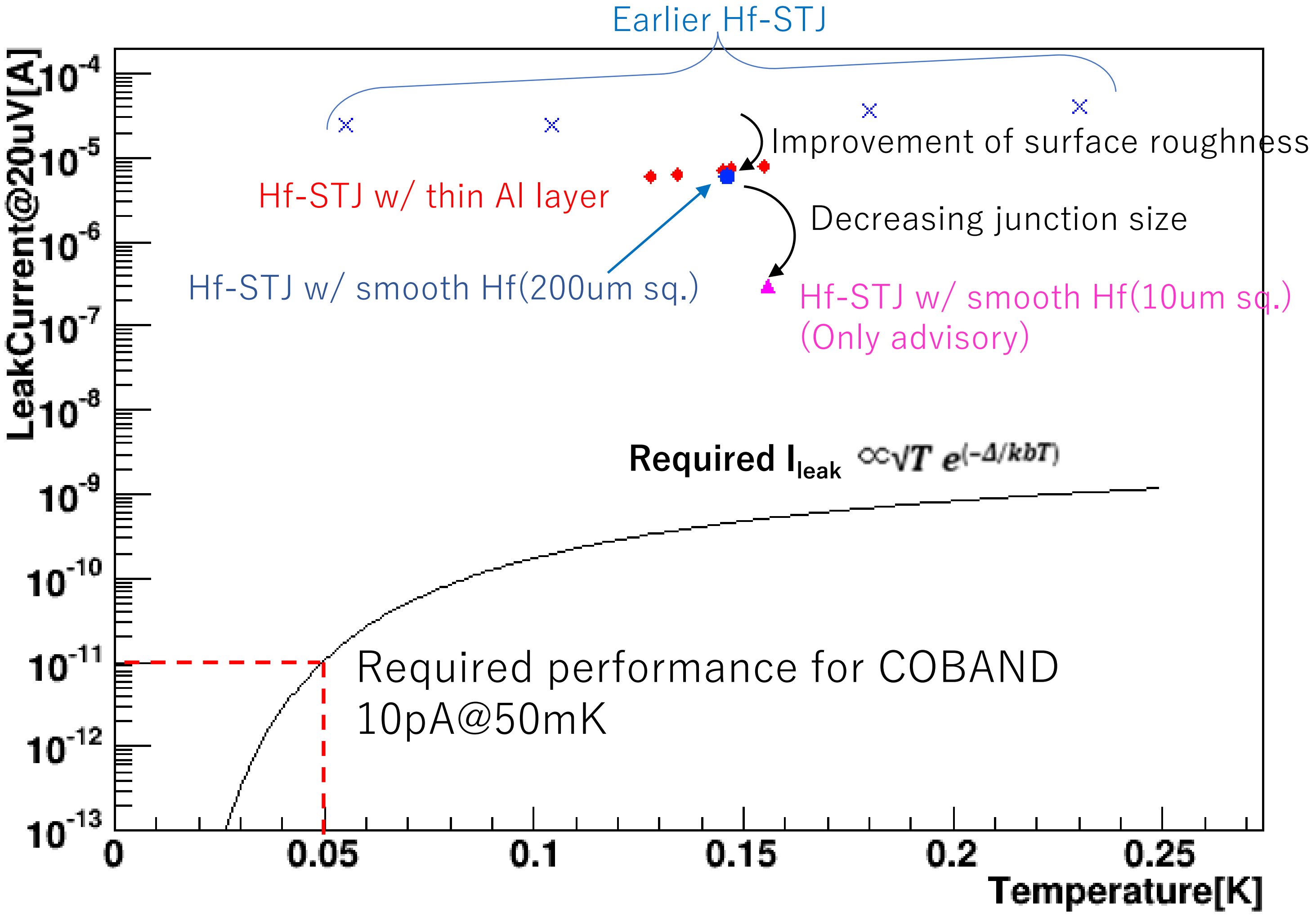
- We have not measured response to light illumination of this STJ yet.







- Leakage current is reduced by improvement of roughness of Hf layer and decreasing junction size.
- However, leakage current is still large, need more improvement.
- We plan to reduce leakage current by changing oxidation parameter or method.



- 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.

Summary

- We are developing Hf-STJ for COBAND satellite experiment.
- Our Hf-STJ works as STJ photon detector.
- Leakage current is reduced by improvement of roughness of Hf surface and downsizing.
  - Roughness of Hf surface : 3 times smaller than old sample.
  - Decrease junction size to 10um sq. : 23 times smaller than 200um sq. STJ.
- However, leakage current is still large, need more improvement.