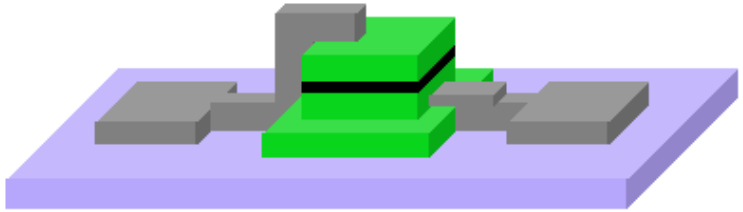
R&D status of Hf-STJ

Kenichi Takemasa (Univ. of Tsukuba)

For COBAND collaboration

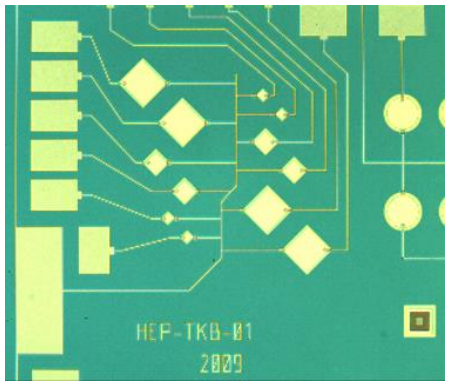
新学術領域研究「ニュートリノフロンティアの融合と進化」研究会2017

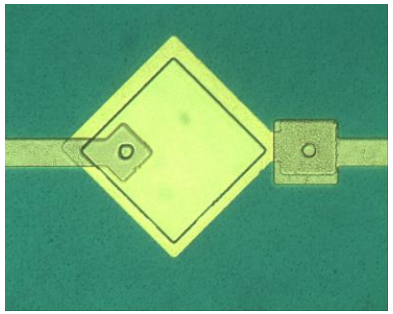
STJ (Superconducting Tunnel Junction) Detector



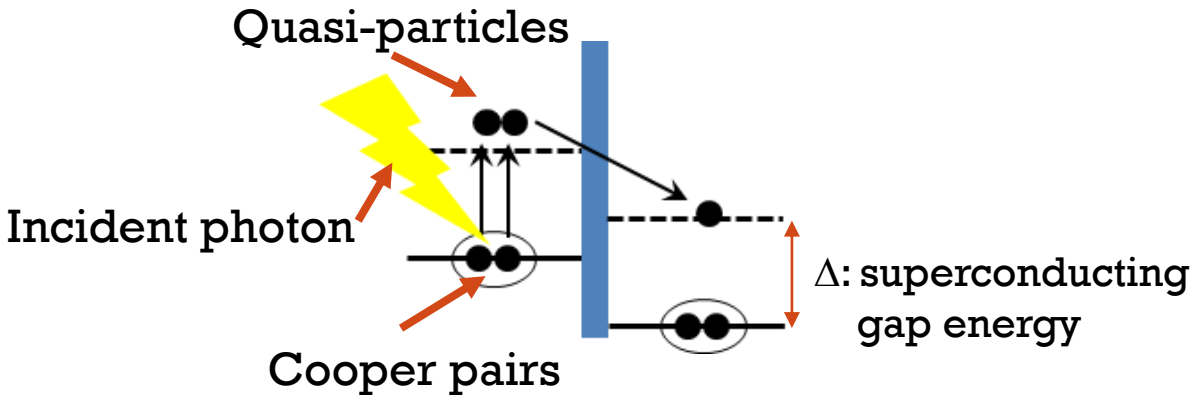
Overhead view of STJ detector

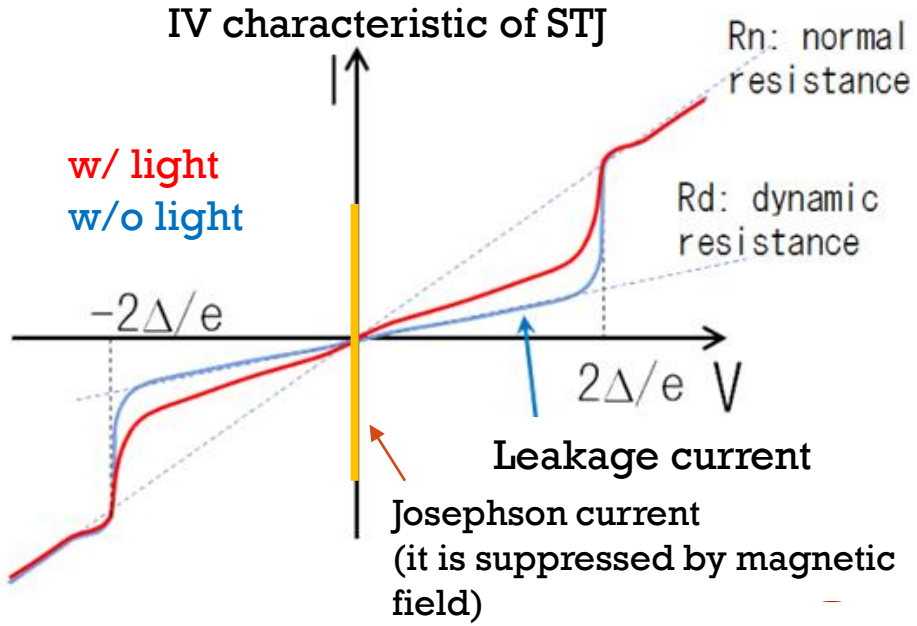
- **Structure**
  - STJ is a type of Josephson junction composed of Superconductor/Insulator/Superconductor
  - Size: dozens～hundreds μm square and 500 nm height





- **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.





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.

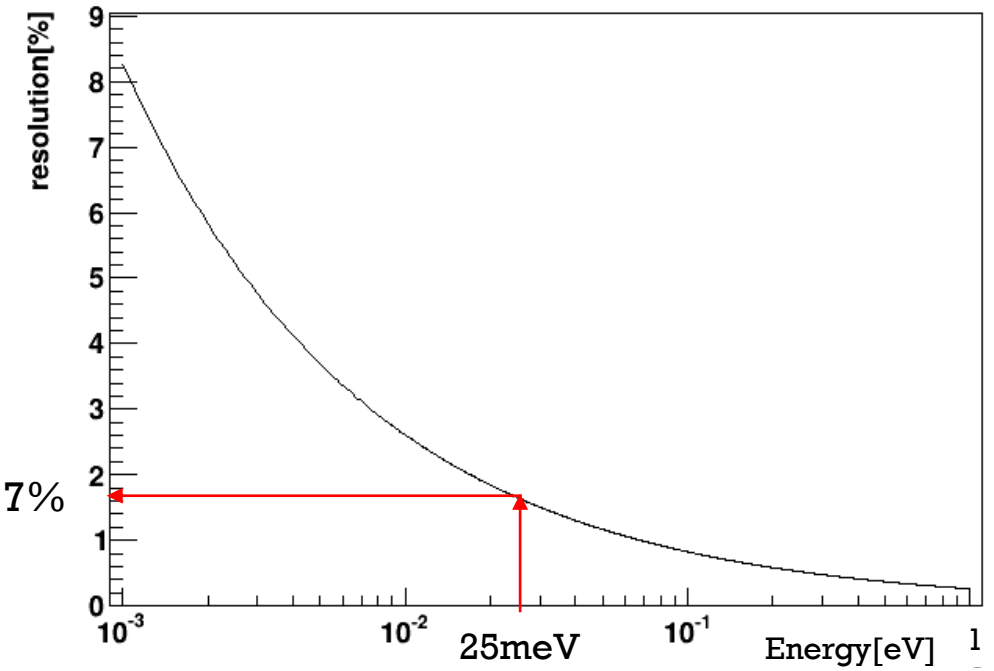
$$\sigma_E/E = \sqrt{(1.7\Delta)F/E}$$

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/1.7Δ =735
- 2% energy resolution is achievable because Δ_{Hf} is very small.

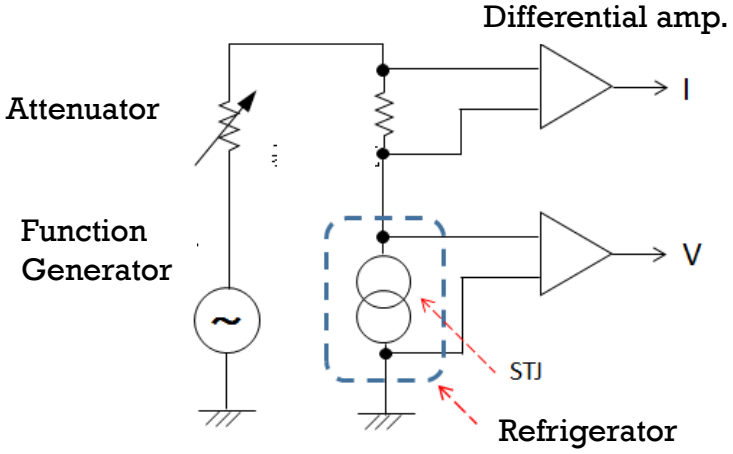
Development environment

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:

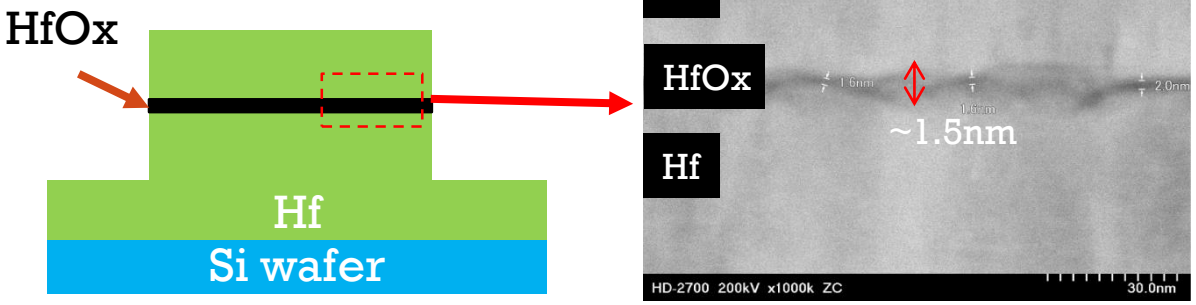
- measure IV characteristic and light response.
- T~120mK using a dilution refrigerator.
  - This refrigerator could provide 15 mK.
  - Now it is out of condition,
    achieving temperature is ~120mK

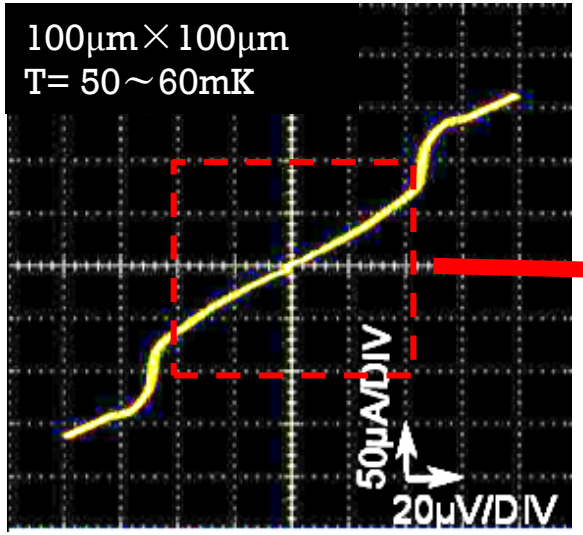


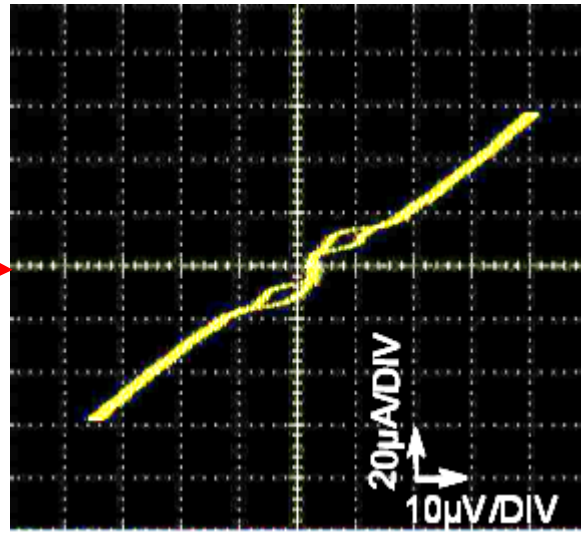
Earlier version of Hf-STJ

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

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

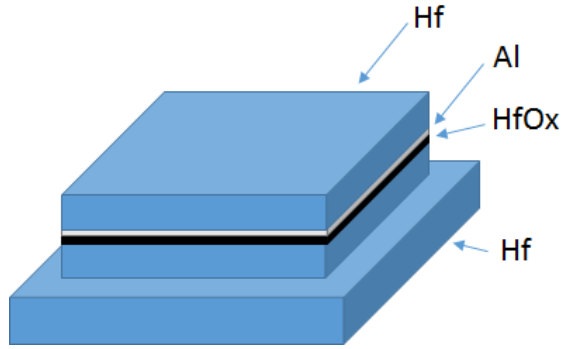


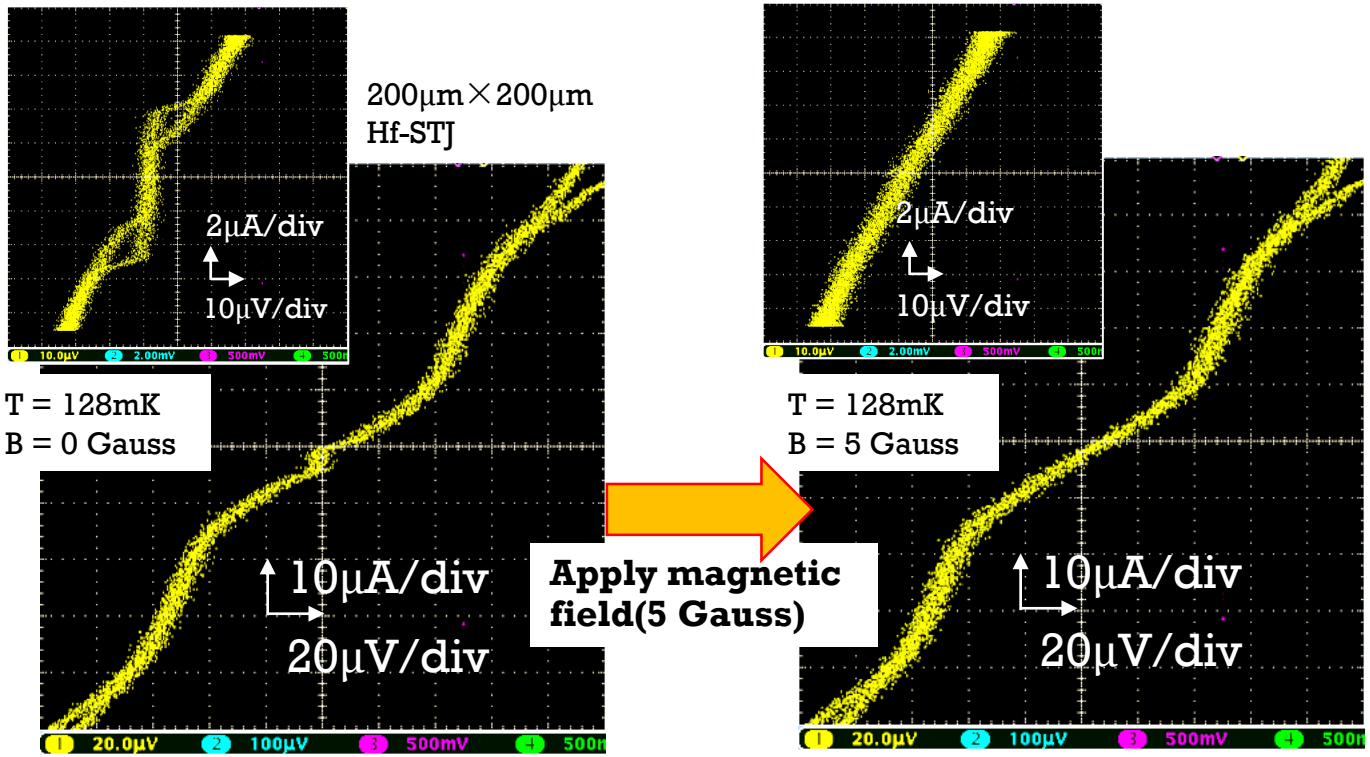


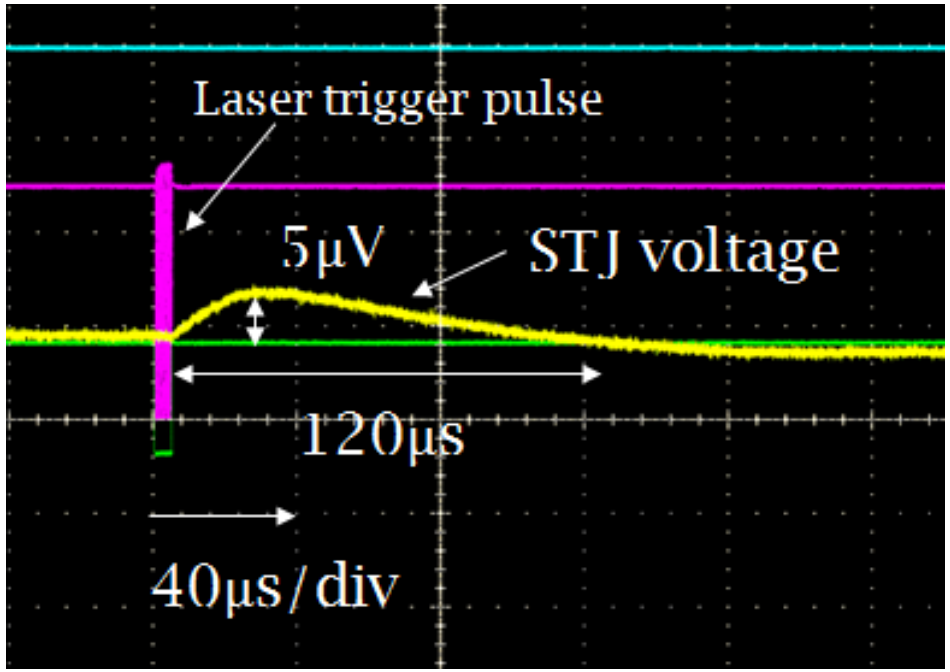


Earlier version of Hf-STJ (Hf-STJ w/ thin Al layaer)

- 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.
  - Δ = 20~30μeV.
  - I_{leak} = **5μA**@128mK (200μm × 200μm sample)
  - **Response to visible laser pulses is observed.**
  - But leakage current is still large. Need more improvement.





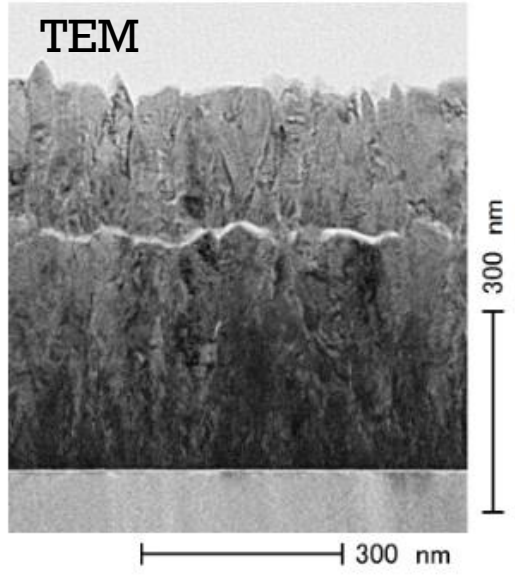


Response to laser pulses

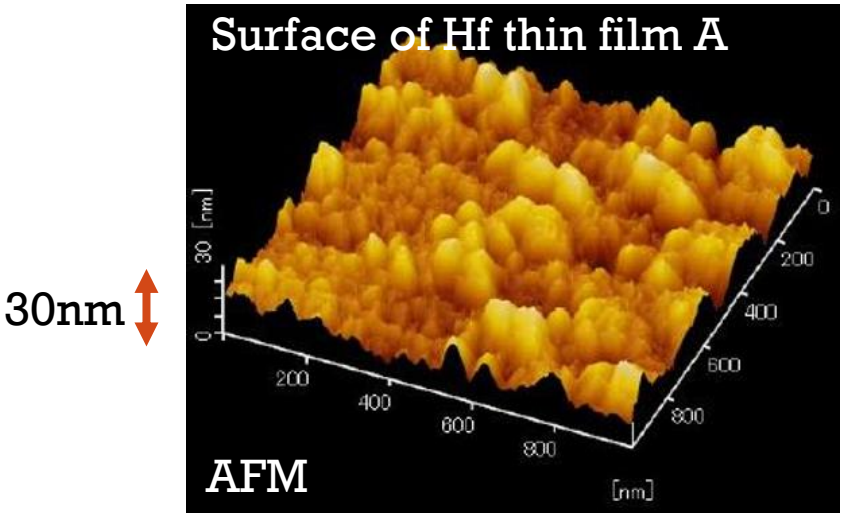
- λ=465nm

Improvement of surface roughness of Hf thin film

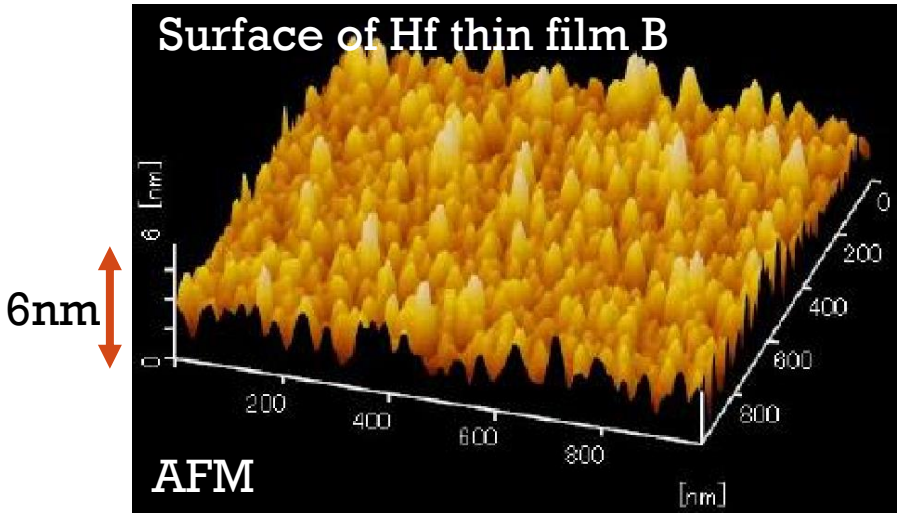
- Hf surfaces of earlier Hf-STJs are very rough.
- Rough surfaces of Hf layer cause defects of insulator.
- To reduce leakage current, we modified the sputtering condition to make smooth Hf layers.
- Target value of RMS of surface roughness < 1nm.
  - RMS should be smaller than thickness of HfOx (~1.5nm).



Sputtering condition A: Ar 2.0Pa, 70W
RMS of surface roughness = 2.5 nm



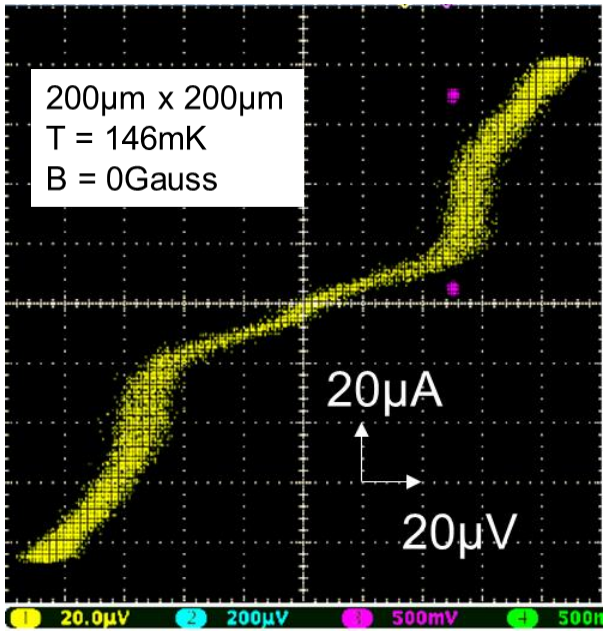
Sputtering condition B: Ar 0.5Pa, 50W
RMS of surface roughness = 0.96 nm



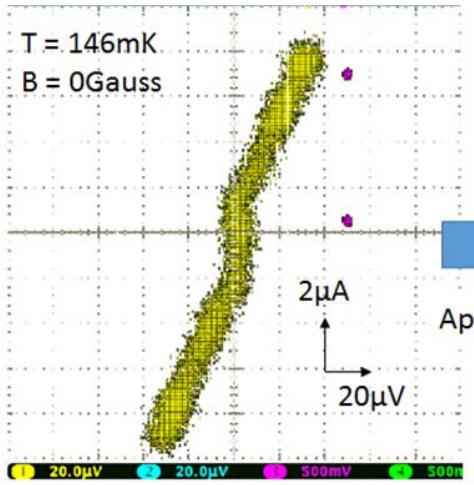
We made Hf-STJs using these Hf thin films.

Hf-STJ using sputtering condition A (RMS=2.5nm)

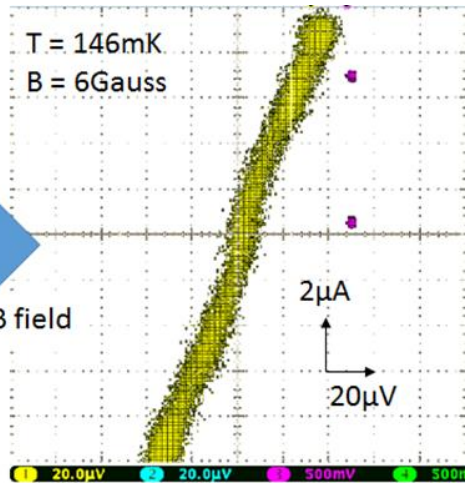
- Josephson current is observed (~2μA). But very small.
- Δ~25μeV.
- Leakage current: 7μA@20μV
  - 3 times smaller than old Hf-STJ. Improved but still large.
- Response to visible light is observed. 7μA increase by light illumination.



IV characteristic

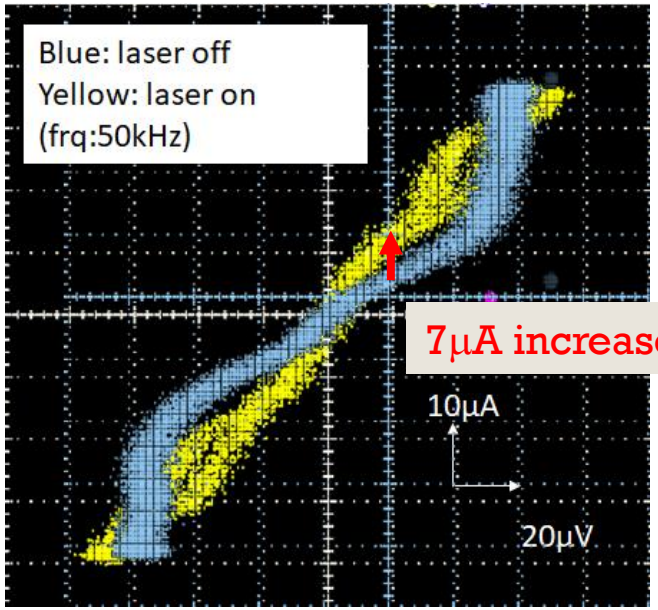


IV characteristic
(near 0V, B=0Gauss)



IV characteristic
(near 0V, 6Gauss)

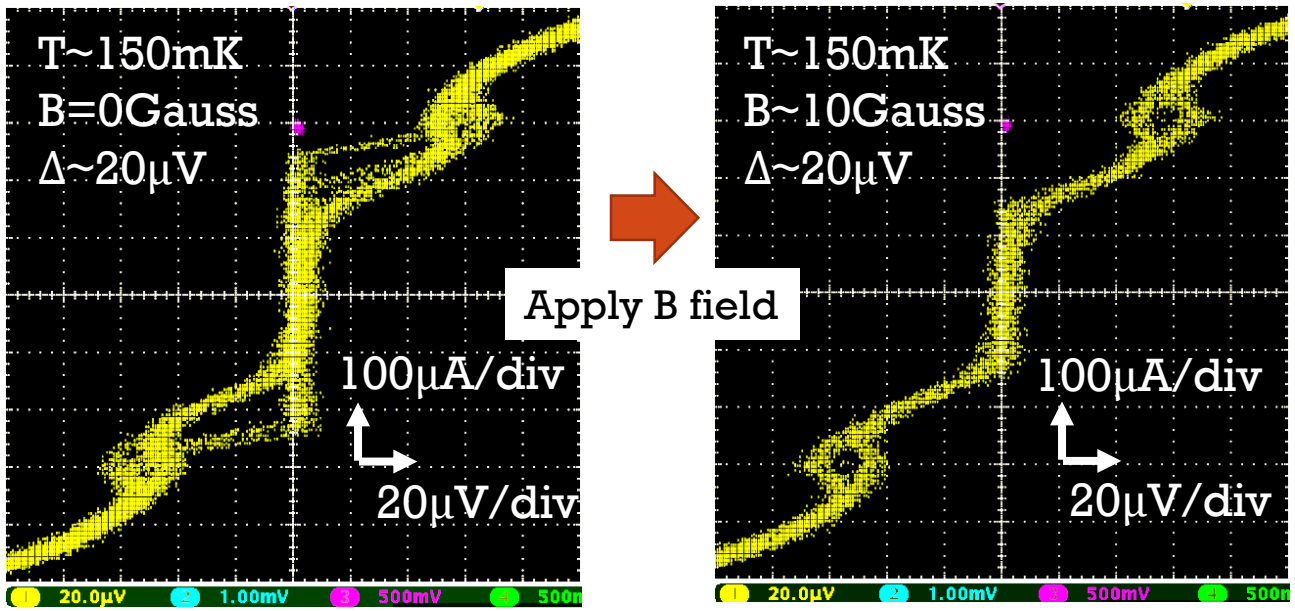
Apply B field

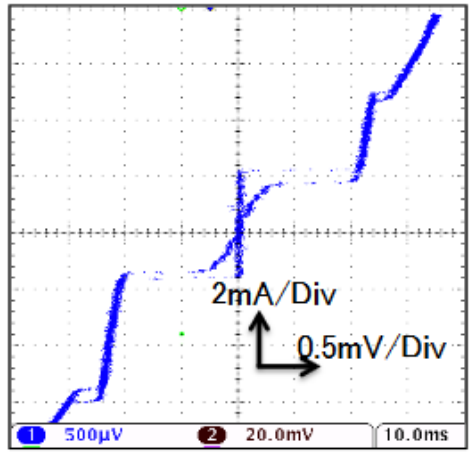


Response to visible(λ=465nm) DC-like laser light
T = 140mK, 9Gauss B field is applied.

Hf-STJ using sputtering condition B (RMS=0.96nm)

- Josephson current is observed: ~250μA
- Δ~25μeV
- Leakage current: ~170μA@20μV
- This Hf-STJ has a shape of IV curve similar to Nb/Al-STJ with insufficient cooling.
- This IV curve is measured at near Tc of Hf. Therefore it has large thermal leakage current.
- If we measure this Hf-STJ at below 0.1Tc, this sample may show a good performance.





IV characteristic of Nb/Al-STJ
@ 3K, B field does not applied.

Improvement plan

- Keep doing the optimization of sputtering condition of Hf film.
- Down sizing
  - Size of previous Hf-STJ is 200um x 200um.
  - We will make 10um x 10um junction
  - 400 times improvement of leakage current is expected.
- Fix a dilution refrigerator to make cryogenic temperature blow 50mK.
  - Reduce thermal leakage current of Hf-STJ.

Summary

- 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.

Thank you for your attention.