TGSW2017
2017/9/26

Status of Photo-Detector Developments Based on STJs for COBAND Project

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For COBAND collaboration

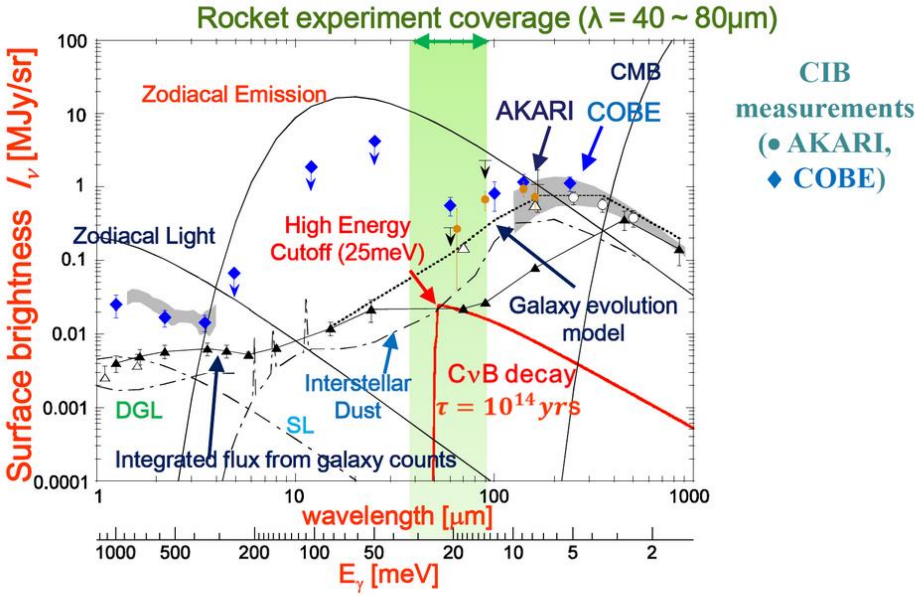
Introduction

- 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

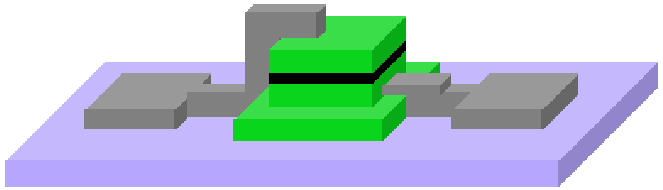
- Requirements for the detector
  - Continuous spectrum of photon energy around E=25 meV(λ=50μm)
  - Energy measurement for a single photon with a better than 2% resolution for E=25meV to identify the sharp edge in the spectrum

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

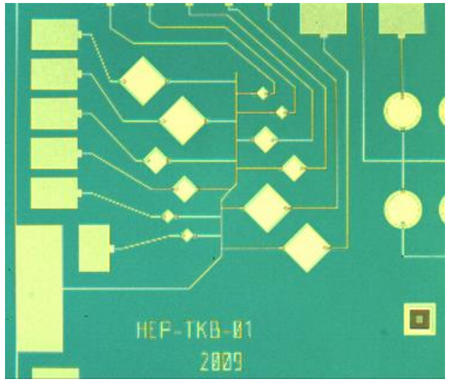


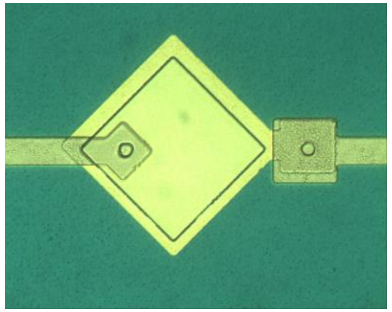
Source: S. Matsuura Astrophys. J. 737 (2011) 2

STJ (Superconducting Tunnel Junction) Detector

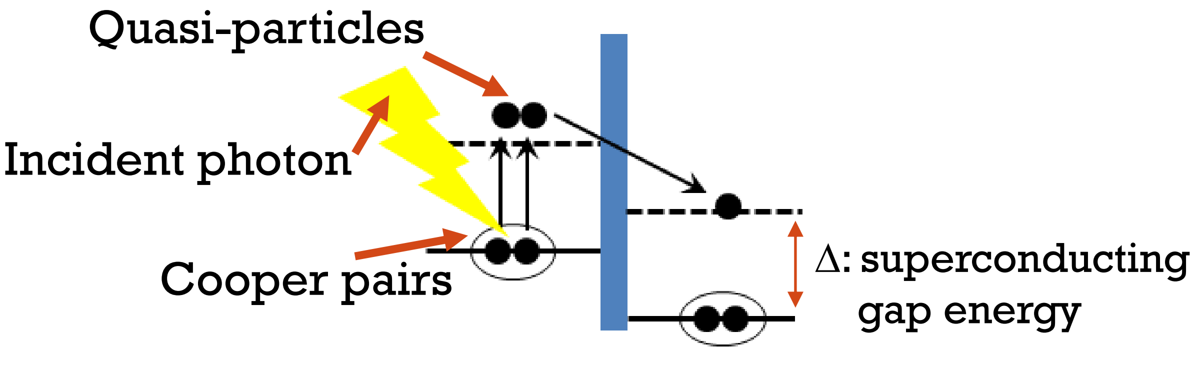


Overhead view of STJ detector

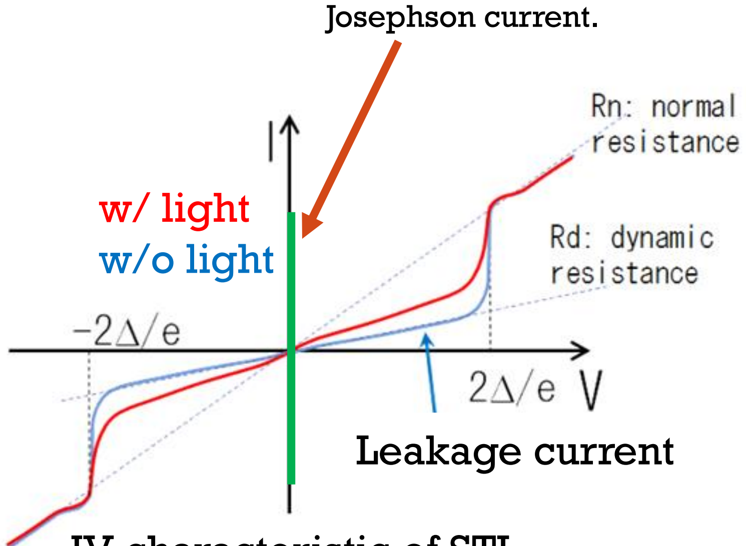




- **Structure**
  - Superconductor/Insulator/Superconductor
  - Size: dozens～hundreds μm square and 500 nm height
- **Working principle**
  - Incident photon is absorbed in the superconductor and excites cooper pairs.
  - Excited cooper pairs become quasi-particles.
  - Quasi-particles go through insulator 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.



Superconductor/Insulator/Superconductor



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)
Si	-	1200
Niobium	9.20	1.550
Aluminum	1.14	0.172
Hafnium	0.16	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
- $N_{q.p.} = 25\text{meV}/1.7\Delta = 9.5$
- poor resolution but counting is possible

Hf

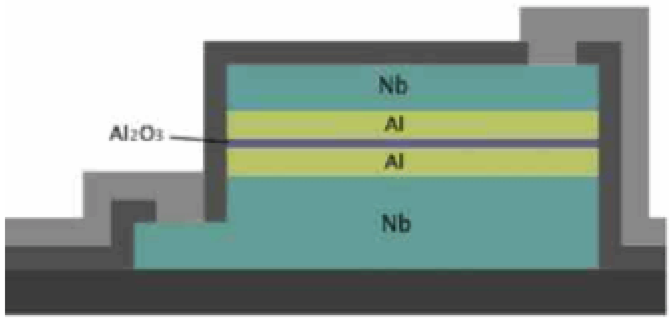
- Hf-STJ as a photon detector is not established
- $N_{q.p.} = 25\text{meV}/1.7\Delta = 735$
- 2% energy resolution is achievable if fano factor <0.3

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 to detect a single far-infrared photon(λ=40-80μm)
  - Measured:

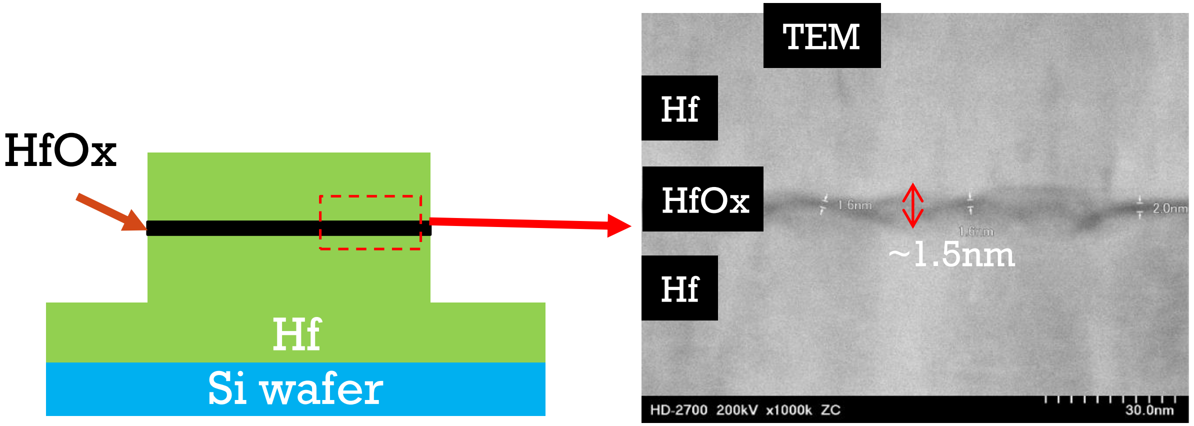
STJ size	# of samples	I_{leak}@0.3mV
20×20μm^2	7	39 ± 13pA
10×10μm^2	20	14 ± 7pA

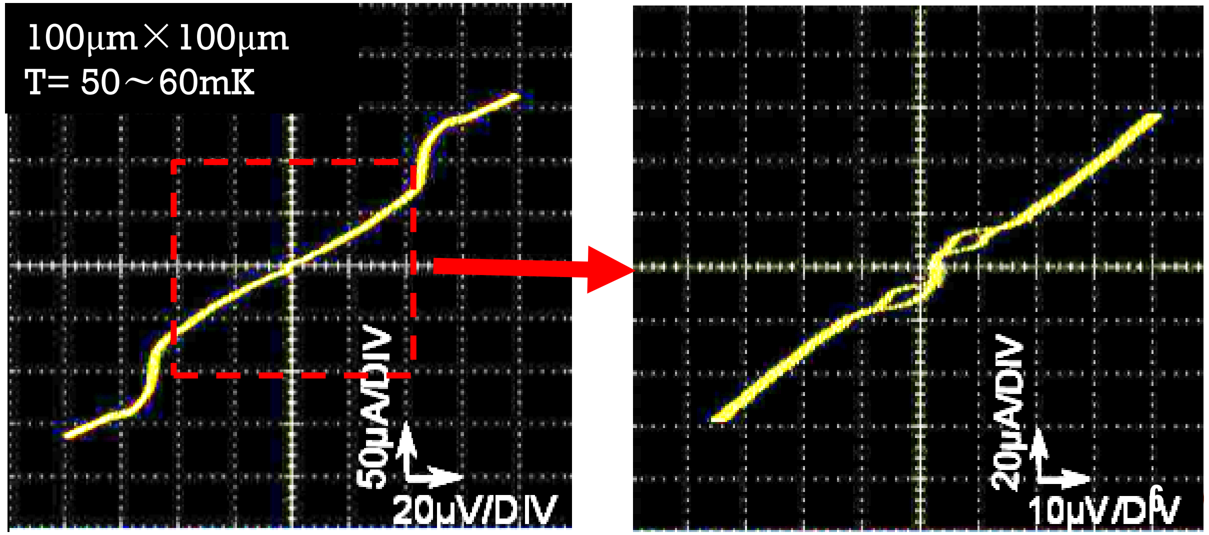
Nb/Al-STJ meets the requirements of the rocket experiment !

Development of Hf-STJ

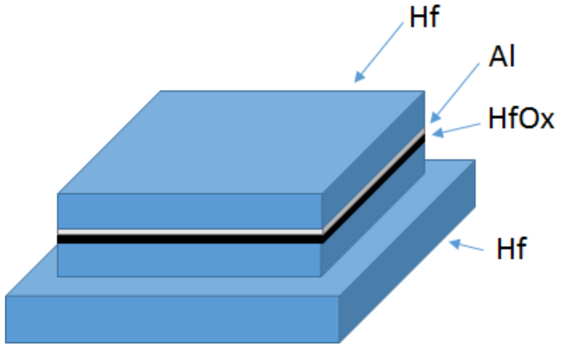
- Earlier version of our Hf-STJ
  - Structure: Hf/HfOx/Hf = 250nm/1.5nm/300nm
  - Δ ~ 20μeV
  - Leakage current at 20μV = 20μA@50mK (100μm sq. sample)

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

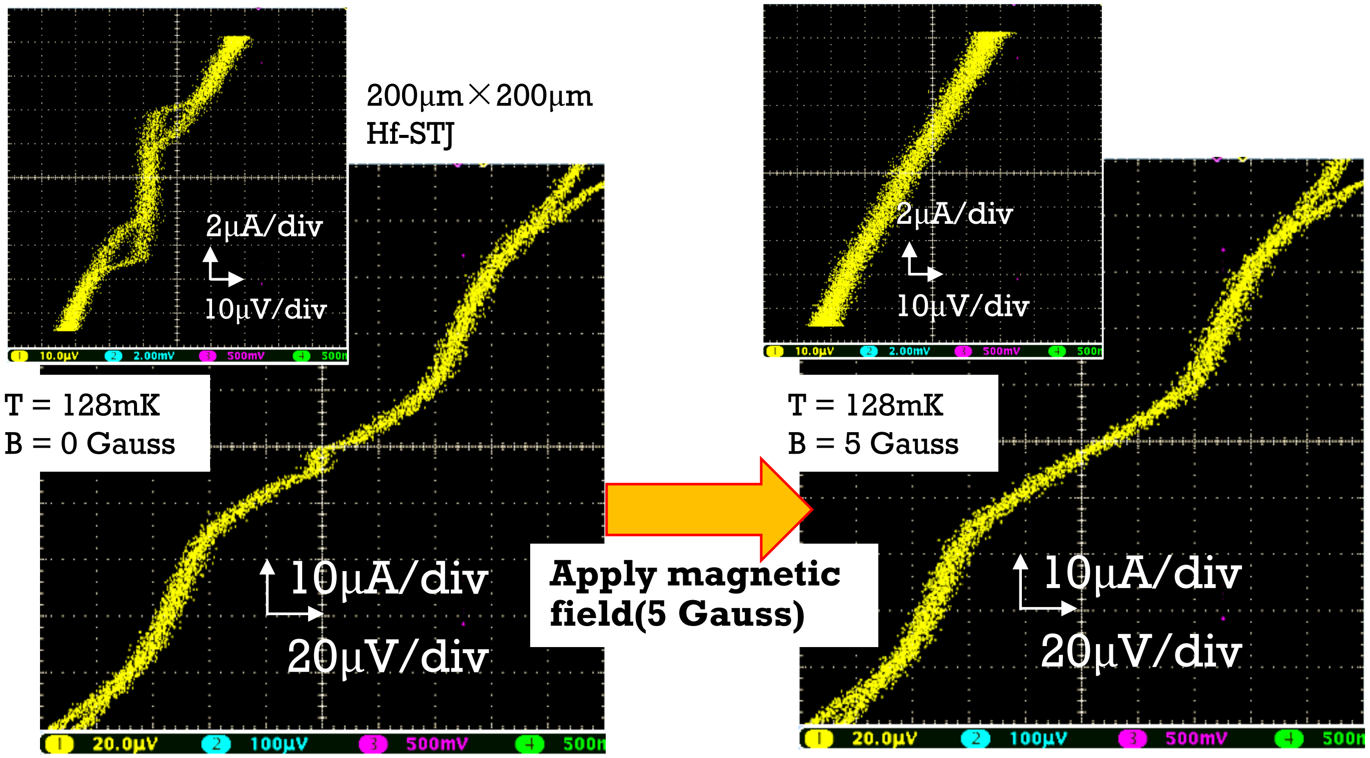


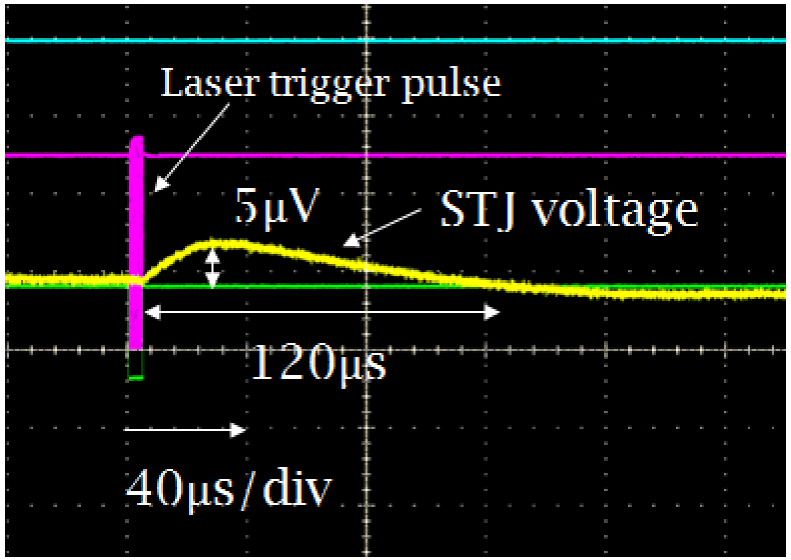


Development of Hf-STJ (Hf-STJ w/ thin Al lyaer)



- 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)
    - I_{leak} becomes 16 times smaller than old sample.
  - **Response to visible laser pulses is observed.**





Response to laser pulses

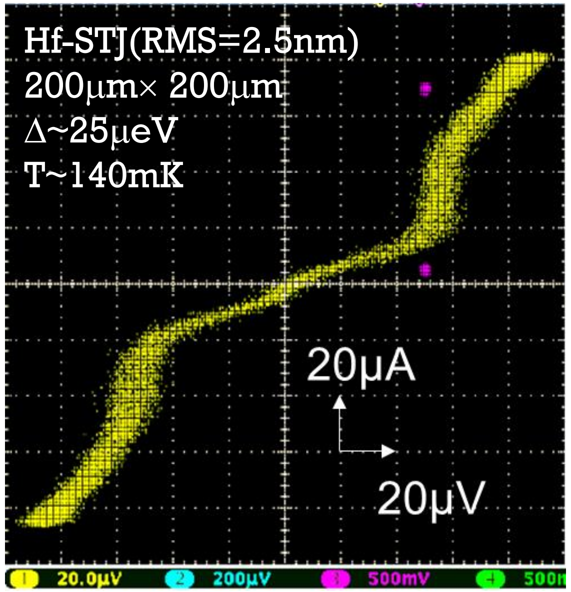
- λ=465nm
- 5MHz oscillation 5μs per 100ms.

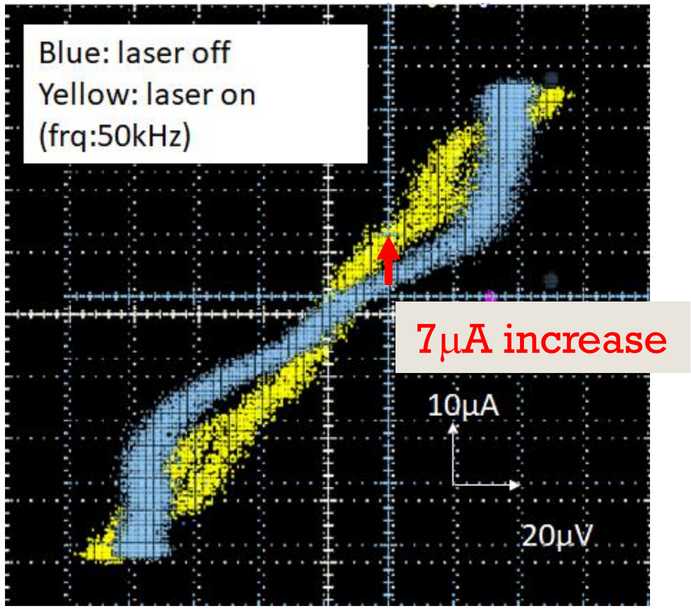
Development of Hf-STJ (pure Hf-STJ)

- To reduce leakage current, We modified the sputtering condition to make smooth Hf layers.
  - Rough surfaces of Hf layer cause defects of insulator.
- We made a Hf-STJ consisting of Hf layers with a small roughness of 2.5 nm RMS deposited a new spattering condition.

Result (200μm sq. sample):

- Leakage current: **6μA** , 16 times smaller than the old Hf-STJ.
- Response to laser continuous illumination is observed.





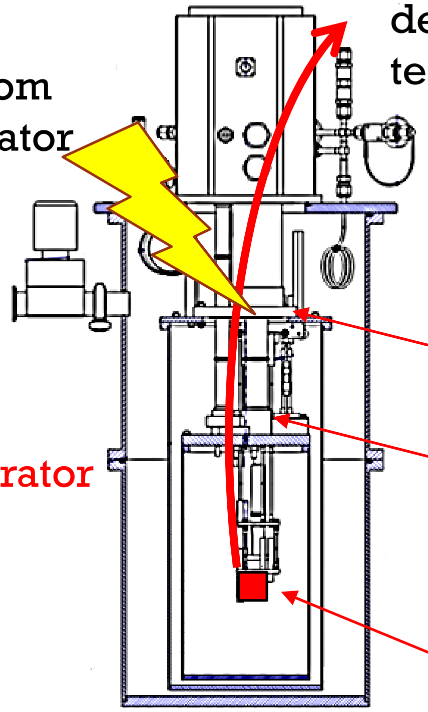
Response to visible(λ=465nm) DC-like laser light
T = 140mK, 9Gauss B field is applied.

This Hf-STJ works as a STJ photon detector.
However, leakage current is still large, need more improvement.

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**
    - To reduce STJ's thermal noise($\propto \sqrt{T}\, e^{(-\Delta/kbT)}$), 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 less than cooling power of our refrigerator
  - **Response speed**
    - The integration time of charge of Nb/Al-STJ is a few μs.
    - Amplification gain should be large enough up to 1MHz.

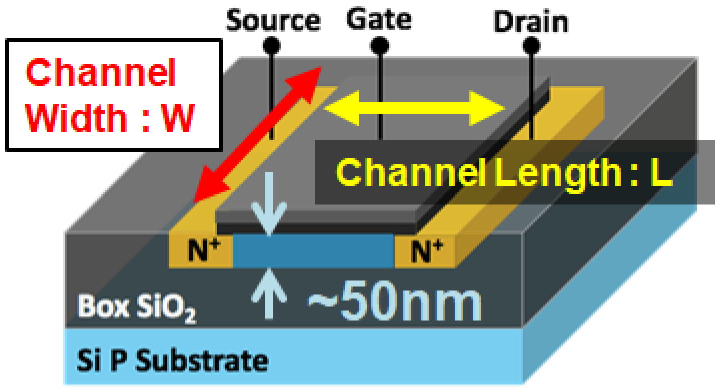


→ Cold amplifier using SOI(Silicon-On-Insulator) technology can achieve these requirements

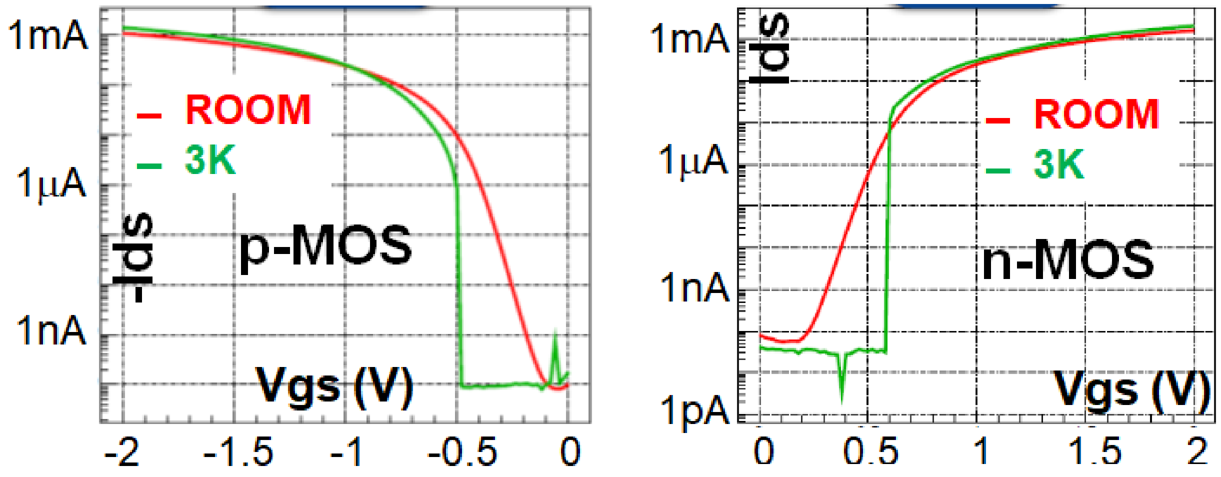
SOI (Silicon-On-Insulator) device

- 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)

FD-SOI-CMOS



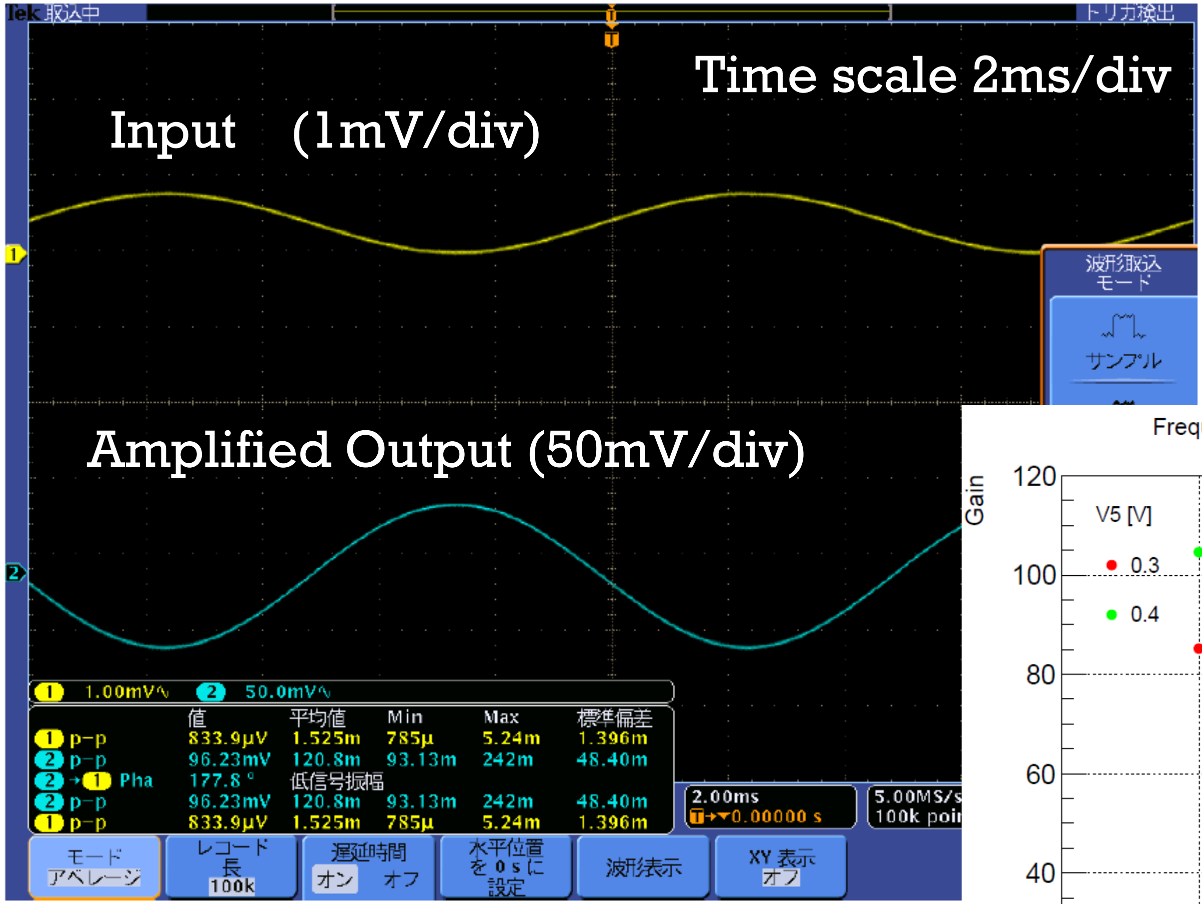
Id-Vg curve of W/L=10μm/0.4μm at |Vds|=1.8V

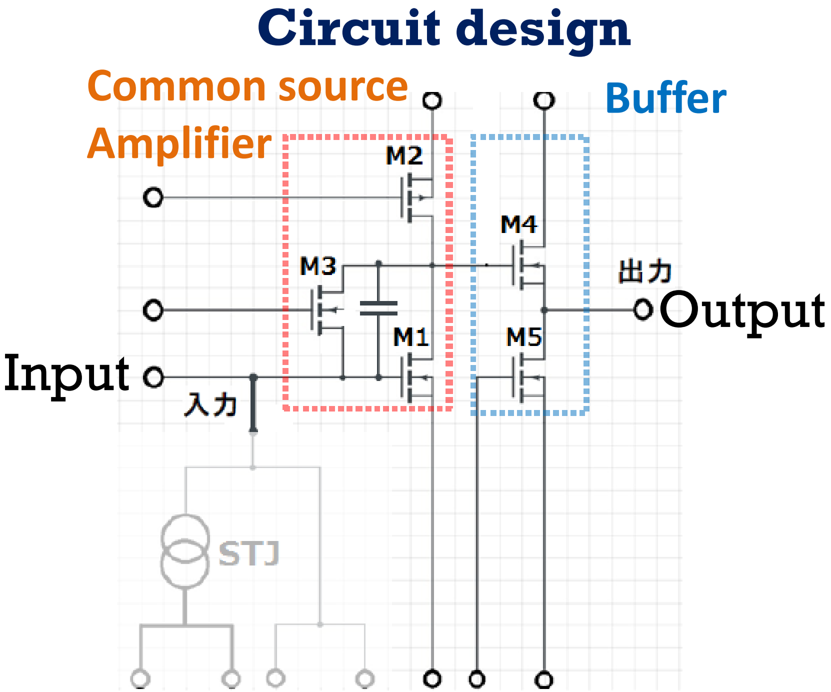


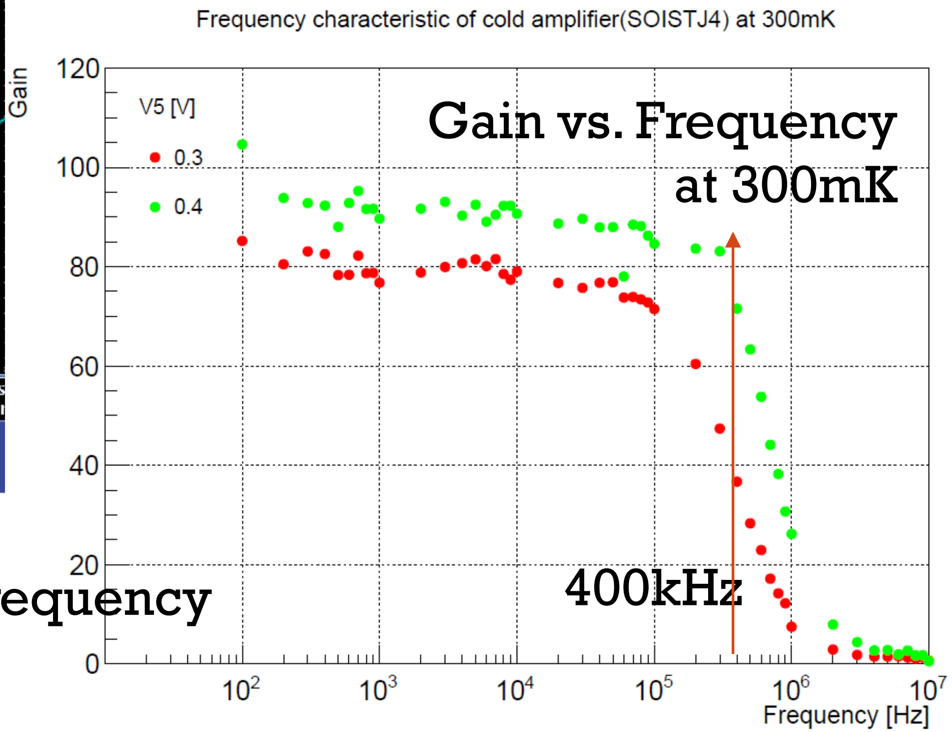
Both p-MOS and n-MOS show excellent performance at 3K and below.

SOI-pre-amplifier 4th prototype

Input and Amplified Output



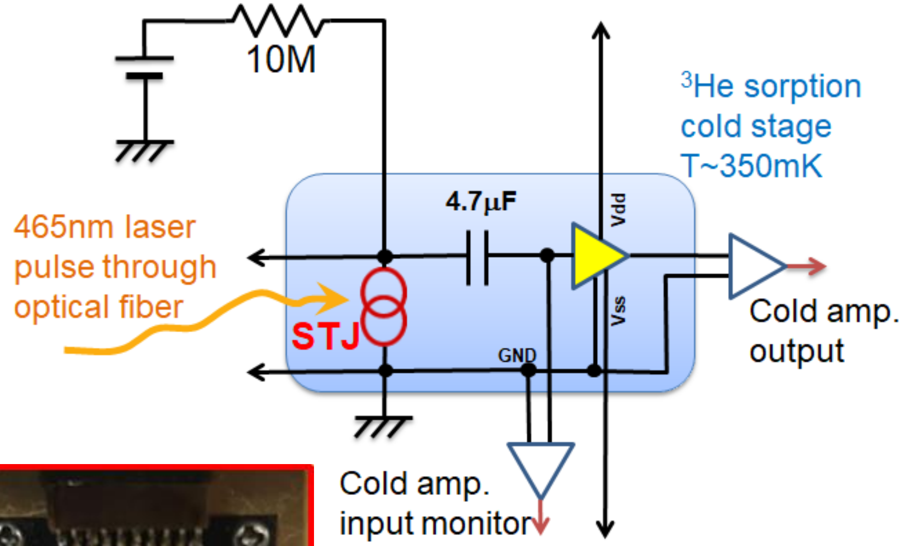


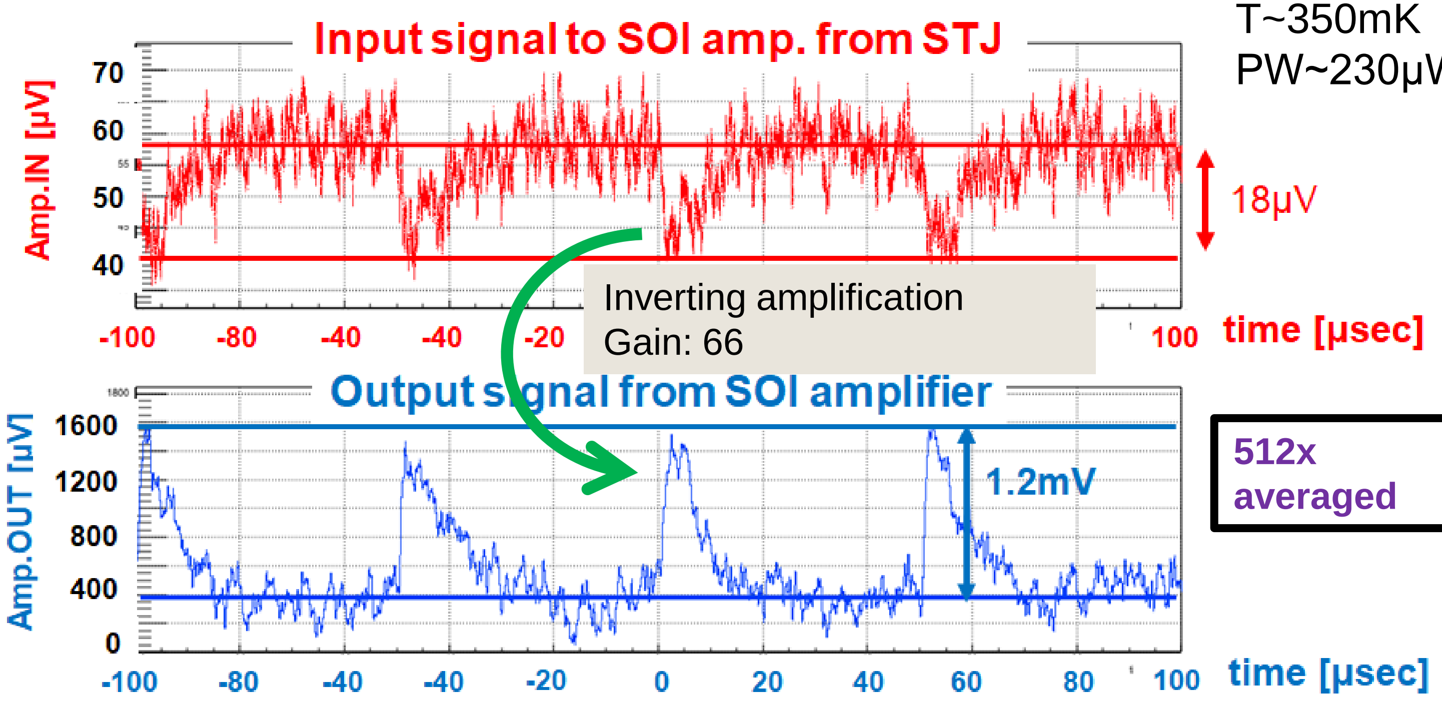


Gain of 80 was achieved for a signal frequency up to 400kHz signals at 300mK.

STJ response to laser pulse amplified by Cold amplifier

- We connect 20μm sq. Nb/Al-STJ and SOI amplifier on the cold stage through a capacitance





T~350mK
PW~230μW

512x averaged

We observe 20μm sq. Nb/Al-STJ responses to laser pulses of λ=465nm amplified by SOI amplifier situated at T=350mK

Summary

- R&D of STJ detectors and SOI-cryogenic amplifier are underway.
- Nb/Al-STJ satisfied our requirement for leakage current less than 0.1nA
- Leakage current of Hf-STJ becomes 1/16 by using smooth Hf layer
- Cryogenic amplifier with the SOI technology worked at 300mK
- We have succeeded in amplifying the STJ signal with the SOI cryogenic amplifier.