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at Beijing International Convention Center

Development of Superconducting Tunnel Junction Photon Detectors with Cryogenic Preamplifier for COBAND Experiment

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for COBAND Collaboration

COBAND Collaboration
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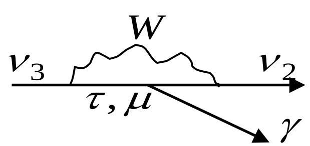
- **Introduction**
  - **Motivation**
  - **COsmic BAckground Neutrino Decay (COBAND) experiment**
- **R&D of Superconducting Tunnel Junction (STJ) Detector**

Motivation of Search for Cosmic Background Neutrino Decay

- **Only neutrino mass is unknown in elementary particles. Detection of neutrino decay enables us to measure an independent quantity of Δm^2 measured by neutrino oscillation experiments. Thus we can obtain neutrino mass itself from these two independent measurements.**



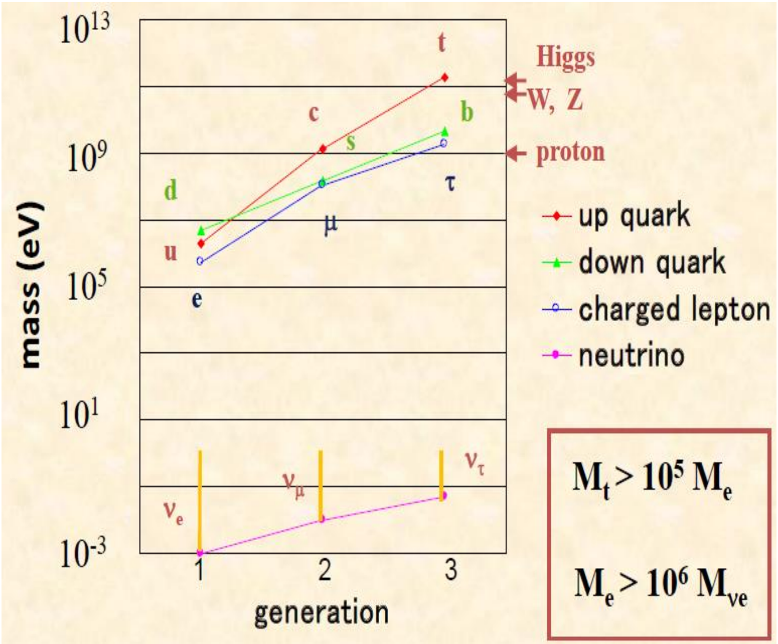
$$\nu_3 \rightarrow \nu_2 + \gamma$$

$$E_\gamma = \frac{m_3^2 - m_2^2}{2m_3} = \frac{\Delta m_{23}^2}{2m_3}$$

Using $\Delta m_{23}^2 = (2.43 \pm 0.09) \times 10^{-3}\,\mathrm{eV}^2$

$E_\gamma = 10 \sim 25\,\mathrm{meV}$ at ν_3 rest frame.

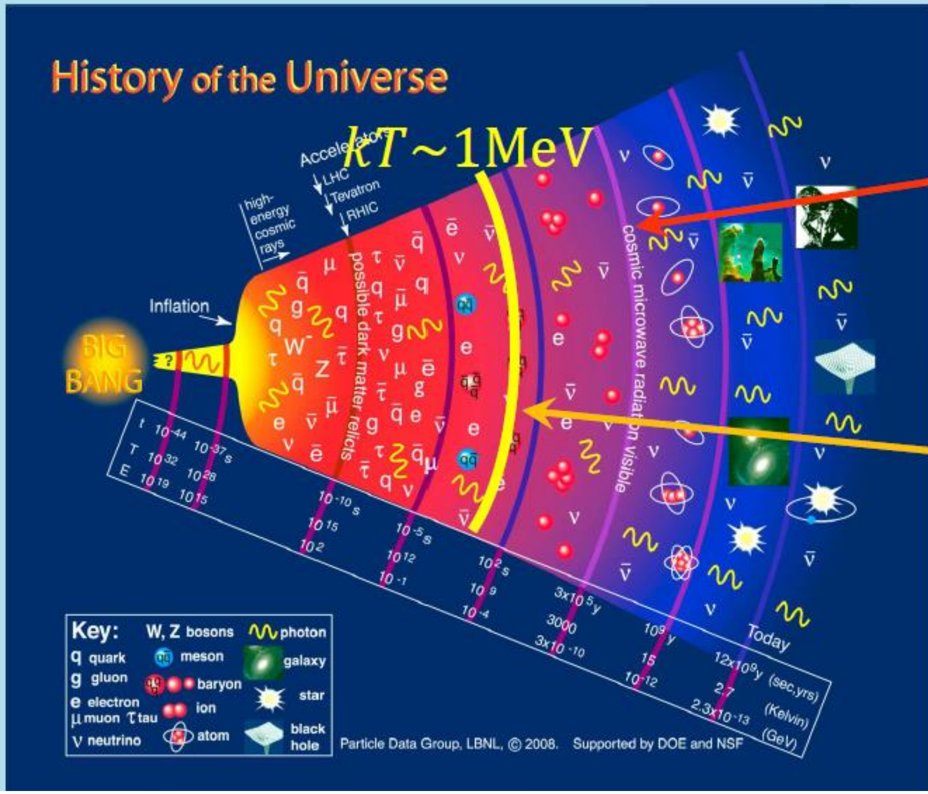
(Far-Infrared region $\lambda = 50 \sim 125\,\mu$)

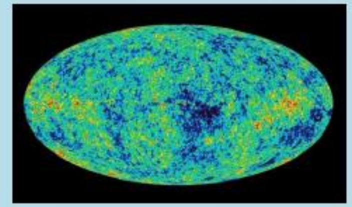


- **As the neutrino lifetime is very long, we need use cosmic background neutrino to observe the neutrino decay. To observe this decay of the cosmic background neutrino means a discovery of the cosmic background neutrino predicted by cosmology.**

- **Left-Right symmetric model predicts the neutrino lifetime larger than 10^{17} year while the standard model predicts 2 x 10^{43} year.**
  Measured neutrino lifetime limit τ > 3 x 10^{12} year.

Big-Bang Cosmology and Cosmic Background Neutrino (CνB)





CMB

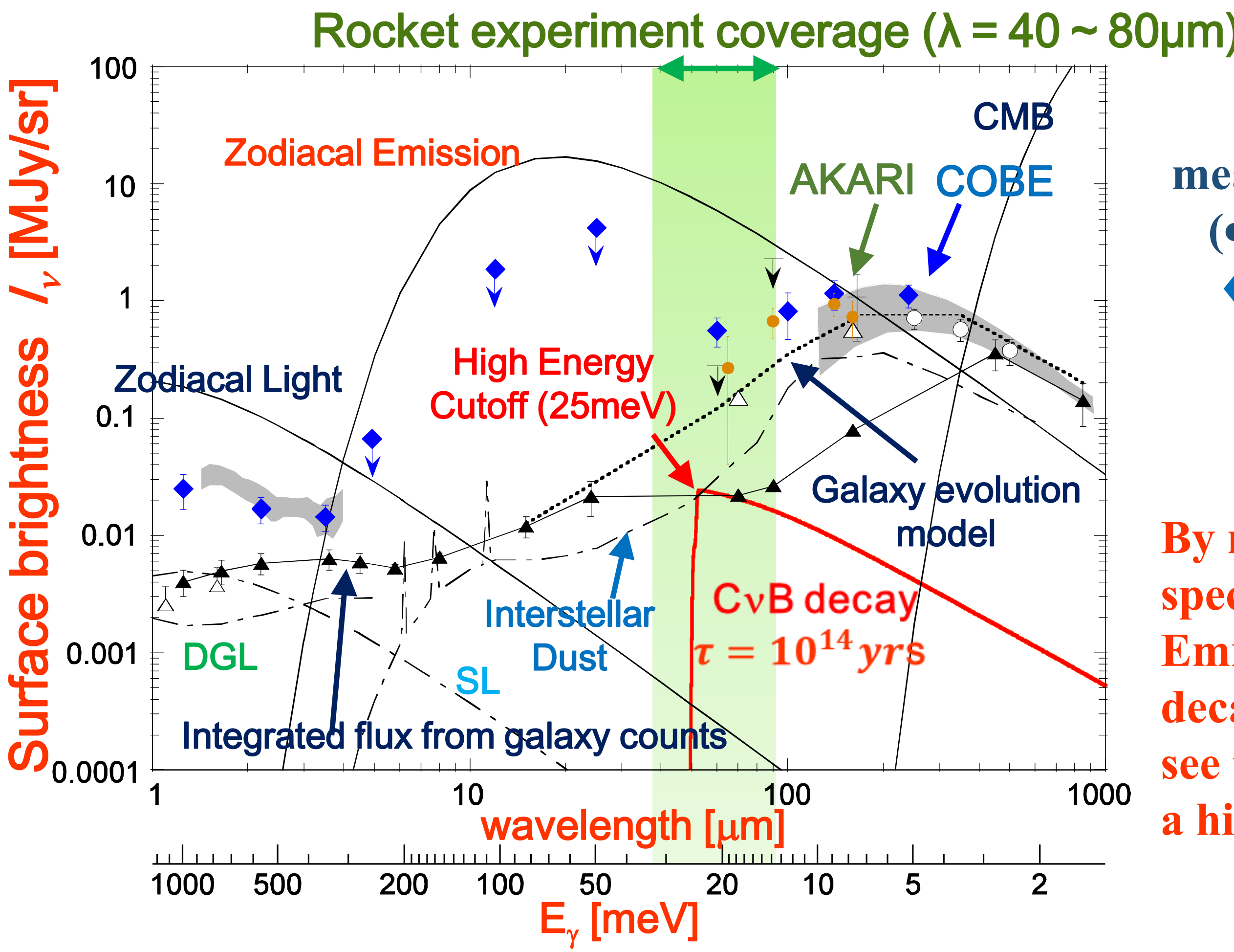
$$n_\gamma = 411/\text{cm}^3$$
$$T_\gamma = 2.73\ \text{K}$$

CνB

$$n_\nu = n_{\bar\nu} = \frac{3}{4}\left(\frac{T_\nu}{T_\gamma}\right)^3 \frac{n_\gamma}{2}$$
$$= 56/\text{cm}^3$$
$$T_\nu = \left(\frac{4}{11}\right)^{\frac{1}{3}} T_\gamma = 1.95\text{K}$$

- **A few seconds after Big Bang → Cosmic Background Neutrino (CνB) became free.**
- **300,000 years after Big Bang → Cosmic Microwave Background (CMB) became free.**

Signal of Cosmic Background Neutrino Decay and its Backgrounds



CIB measurements (● AKARI, ◆ COBE)

By measuring the energy spectrum of the Zodiacal Emission with the CνB decay continuously, we can see the CνB decay signal as a high energy cutoff.

Requirements for the detector

- Continuous spectrum of photon energy around $E_\gamma \sim 25\,\mathrm{meV}(\lambda = 50\mu m)$
- Energy measurement for single photon with better than 2% resolution for $E_\gamma = 25\mathrm{meV}$ to identify the sharp edge in the spectrum
- Rocket and/or satellite experiment with this detector

COBAND (COsmic BAckground Neutrino Decay Search) Experiment

Rocket Experiment Plan: 5minutes data acquisition at 200 km height in 2019.

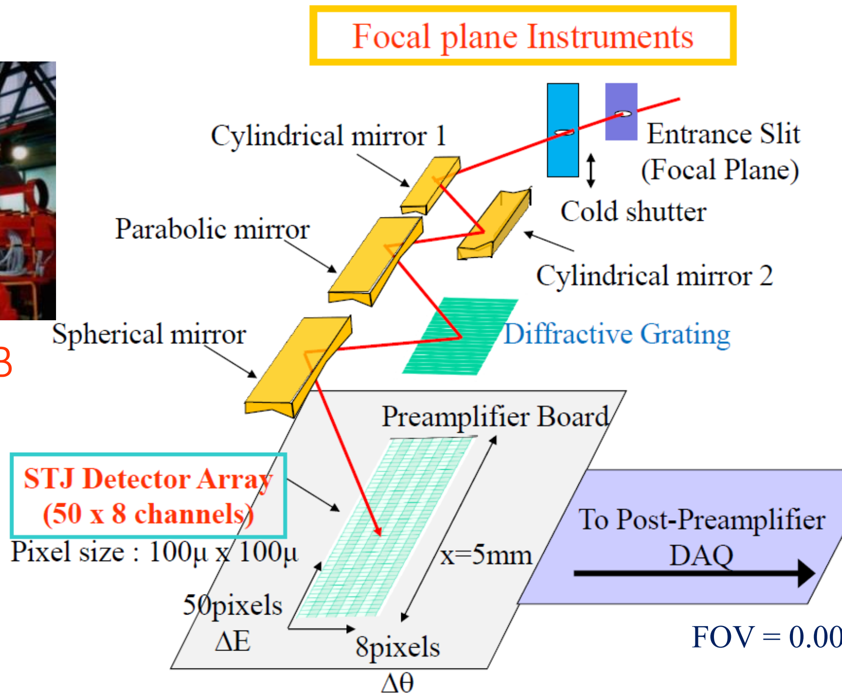
Improve the current limit of lifetime $\tau(\nu_3)$ by two orders of magnitude ($\sim 10^{14}$years).

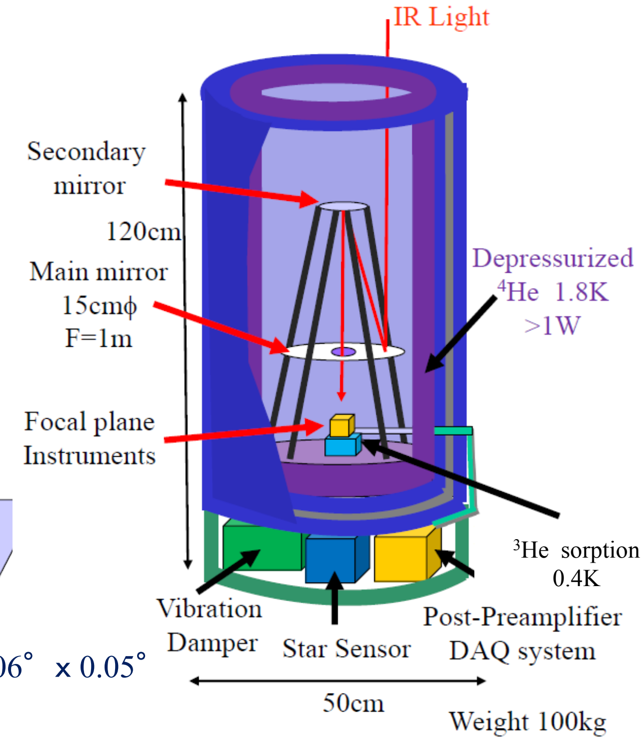
»**Superconducting Tunneling Junction (STJ) detectors in development**

> **Array of 50 Nb/Al-STJ pixels with diffractive grating covering $\lambda = 40 - 80\mu m$**

JAXA Rocket CIB Experiment

(Feb 2, 1992)





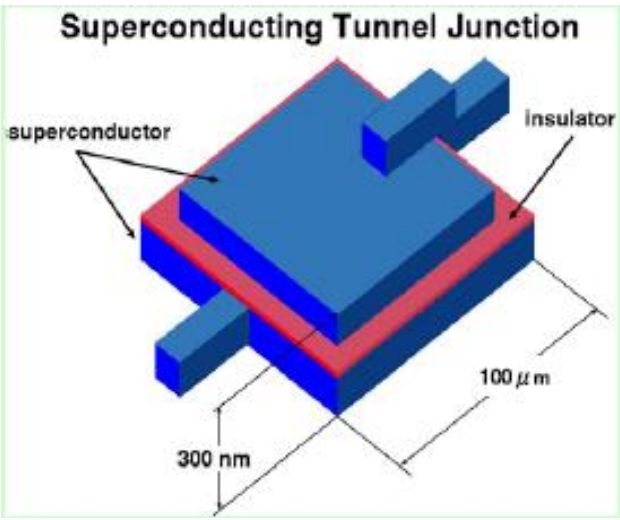
Satellite experiment after 2020 → sensitivity of $\tau(\nu_3) \sim 10^{17}$year

> STJ using Hafnium: Hf-STJ for satellite experiment (S. H. Kim et al. JPSJ 81,024101 (2012))

- $\Delta = 20\mu$eV : Superconducting gap energy for Hafnium
- $N_{\rm q.p.} = 25{\rm meV}/1.7\Delta = 735$ for 25meV photon: $\Delta E/E < 2\%$ if Fano-factor is less than 0.3

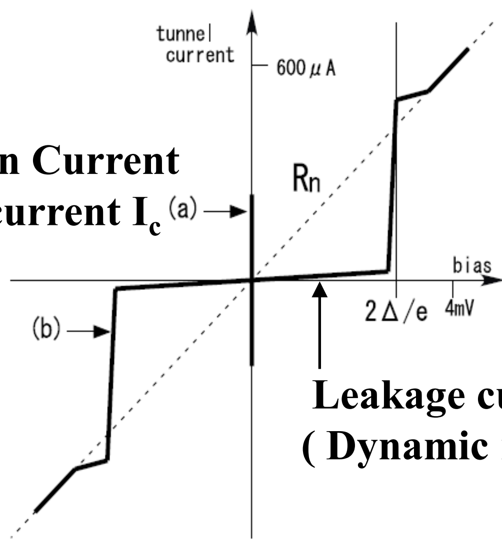
STJ (Superconducting Tunnel Junction) Detector

- Superconductor / Insulator / Superconductor Josephson Junction



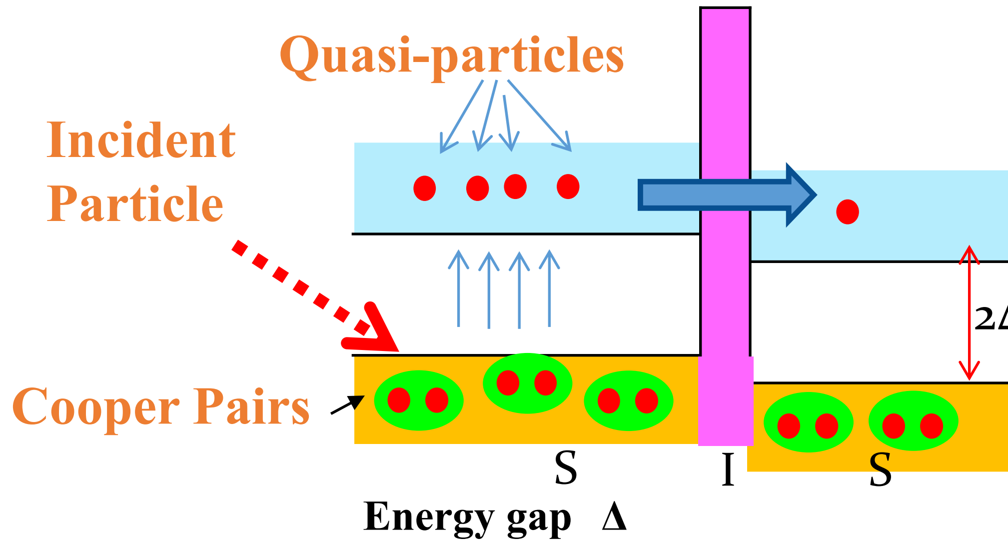
At the superconducting junction, quasi-particles over their energy gap go through tunnel barrier by a tunnel effect. By measuring the tunnel current of quasi-particles excited by an incident particle, we measure the energy of the particle.

current-voltage (I-V) curve for STJ



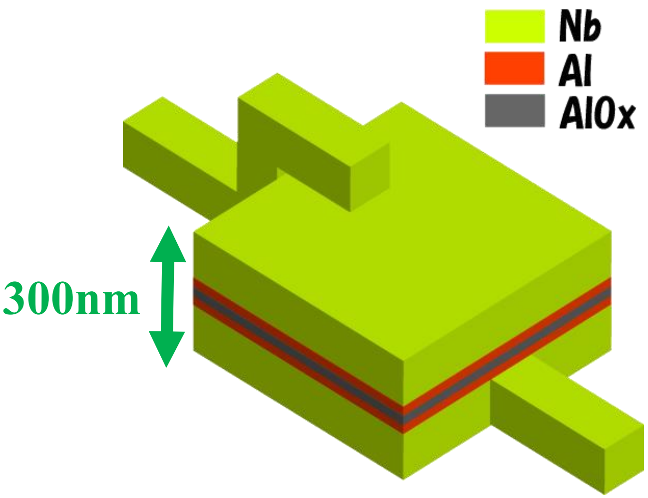
Josephson Current
Critical current I_c

Leakage current
(Dynamic resistance R_d in $|V| < 2\Delta/e$)



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

Nb/Al-STJ Photon Detector



Back tunneling Effect → Trapping Gain

- Quasi-particles near the barrier can mediate Cooper pairs, resulting in true signal gain
  - Bi-layer fabricated with superconductors of different gaps $\Delta_{Nb} > \Delta_{Al}$ to enhance quasi-particle density near the barrier
  - Nb(200nm)/Al(70nm)/AlOx/Al(70nm)/Nb(100nm)

    $\Delta_{Nb/Al} = 0.57\text{meV}$
- Gain: 2～200 (10 for Al)

Number of Quasi-particles in Nb/Al-STJ

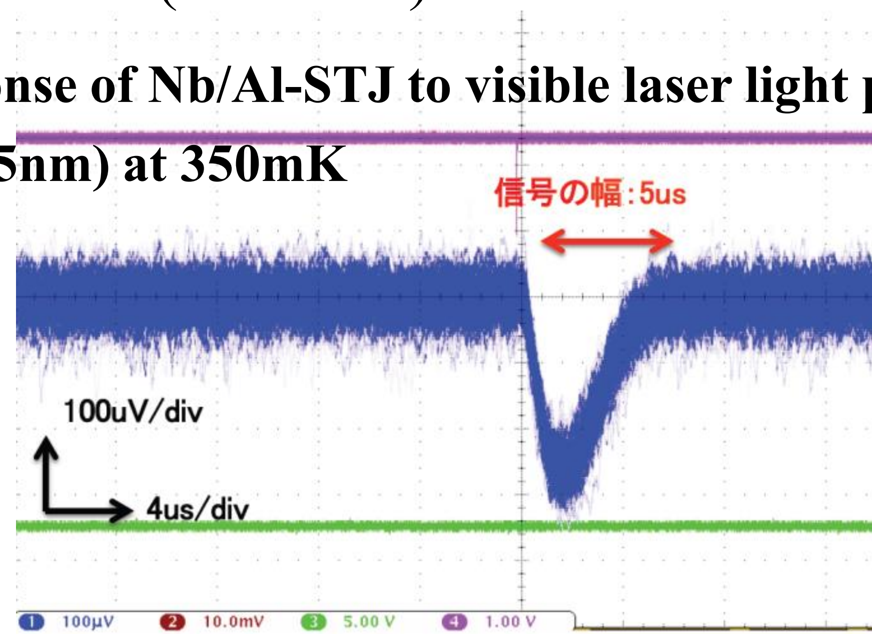
$$N_q = G_{Al} \, {}^{E_0}/_{1.7\Delta}$$

G_{Al} : Trapping Gain in Al(~10)
E_0 : Photon Energy
Δ : E-Gap in superconductor

For 25meV single photon

$$N_q = 10 \frac{25\ meV}{1.7 * 0.57\ meV} = 250\ e$$

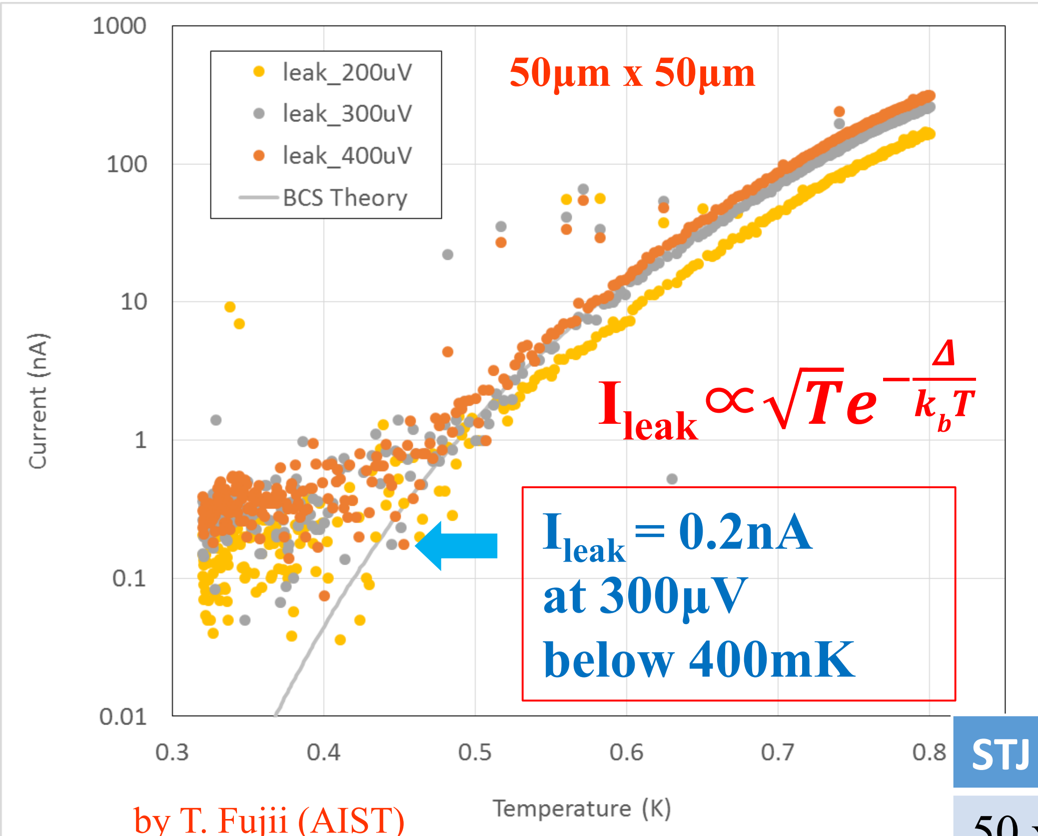
Response of Nb/Al-STJ to visible laser light pulse (λ=465nm) at 350mK



Leakage Current of Nb/Al-STJ

- Leakage current I_{leak} is required to be below 0.1nA to detect a single far-infrared photon (λ= 40 -80μm) .

Temperature Dependence of Leakage Current



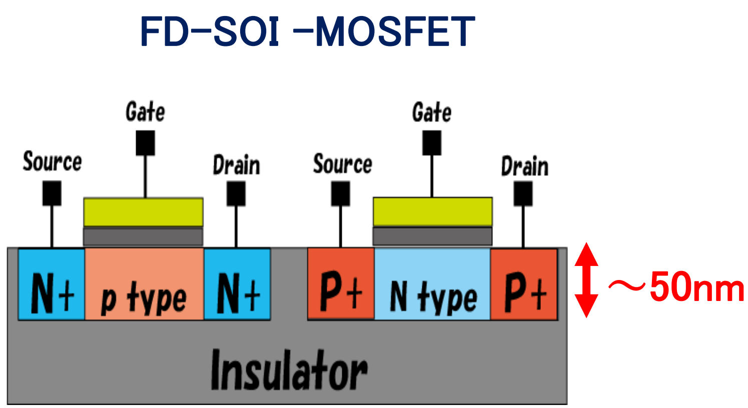
by T. Fujii (AIST)

In 2014,
AIST group joined us and produced Nb/Al-STJ with AIST CRAVITY processing system.
Leakage current has satisfied our requirement of 0.1nA .

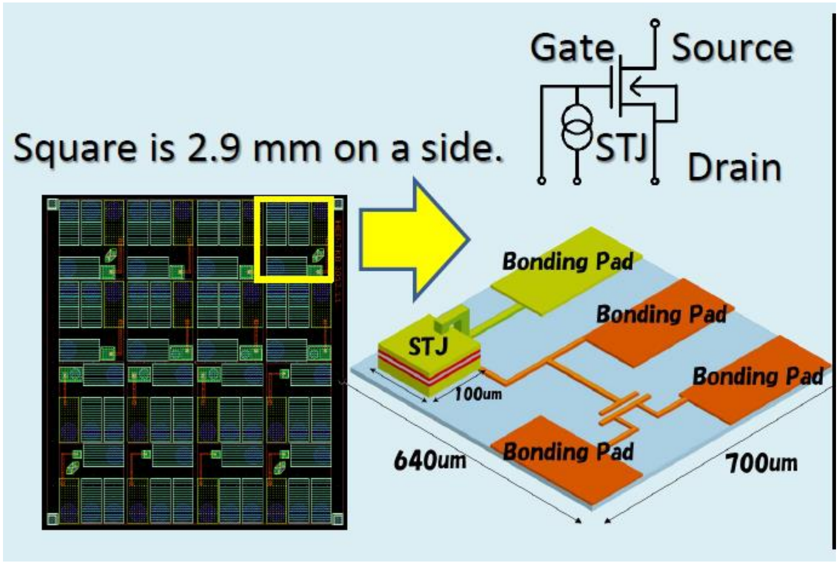
STJ size	# of samples	I_{leak} at 0.3mV
50 x 50μm^2	18	224±29 pA
20 x 20 μm^2	7	**39±13 pA**
10 x 10 μm^2	20	**14±7 pA**

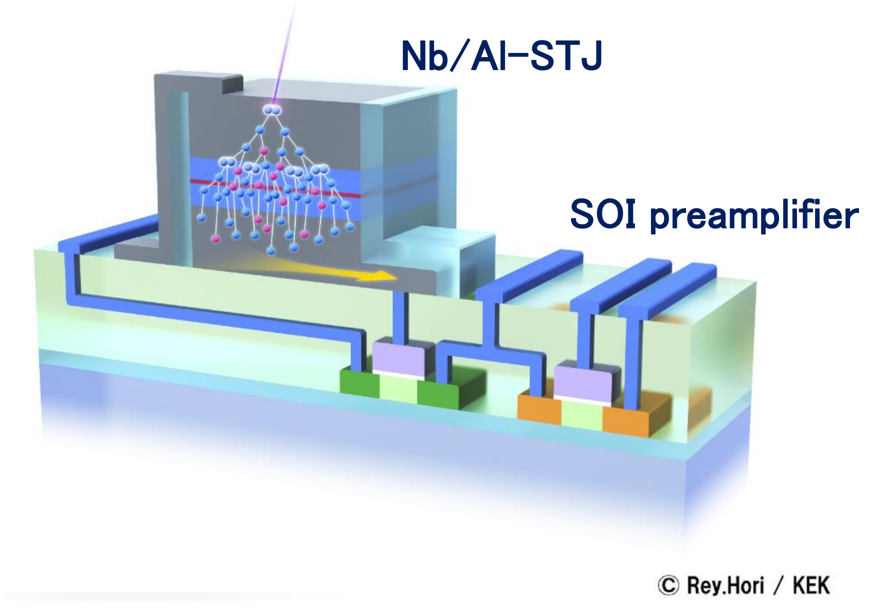
R&D of SOI-STJ Detector

FD-SOI (Fully Depleted Silicon-On-Insulator) device was proved to operate at 4K by a JAXA/KEK group (AIPC 1185,286-289(200 FD-SOI 9)). It has the following characteristics: low-power consumption, high speed, easy large scale integration and suppression of charge-up by high mobility carrier due to thin depletion layer(～50nm).



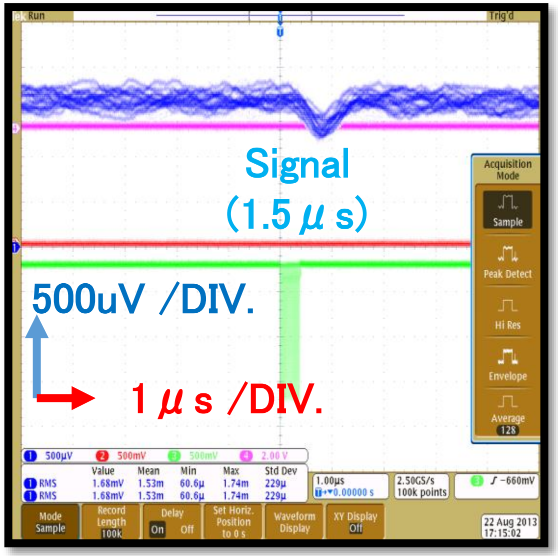
To improve the signal-to-noise ratio and to make multi-pixel device easily, we made a SOI-STJ detector where we processed Nb/Al-STJ on a SOI transistor board.

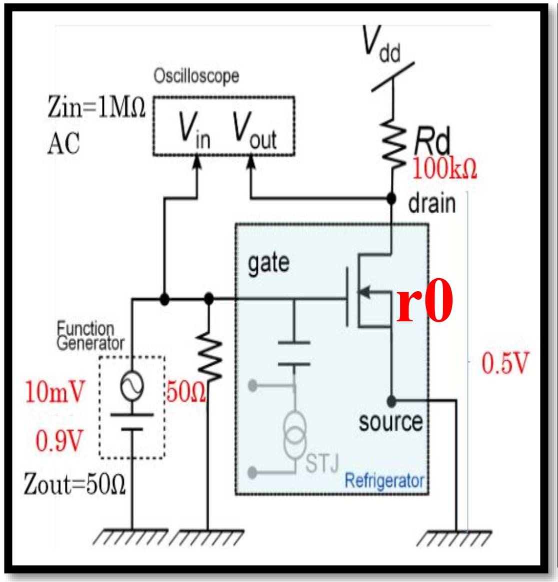


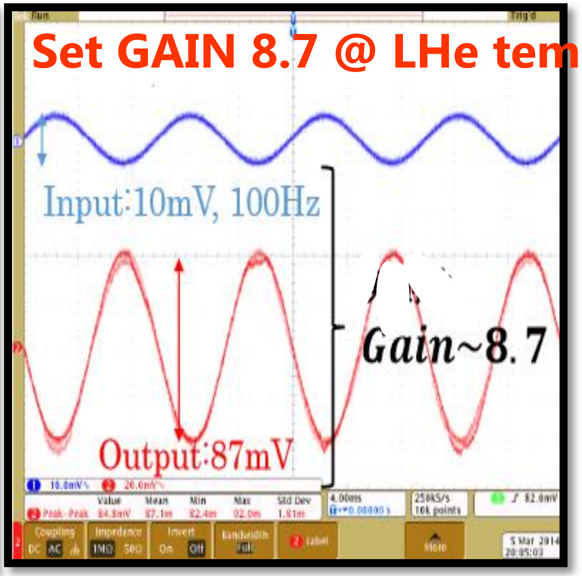


Performance of STJ and SOIFET in SOI-STJ detector

- We observed the signal of Nb/Al-STJ processed on the SOI board to 465nm laser pulse at 700mK.



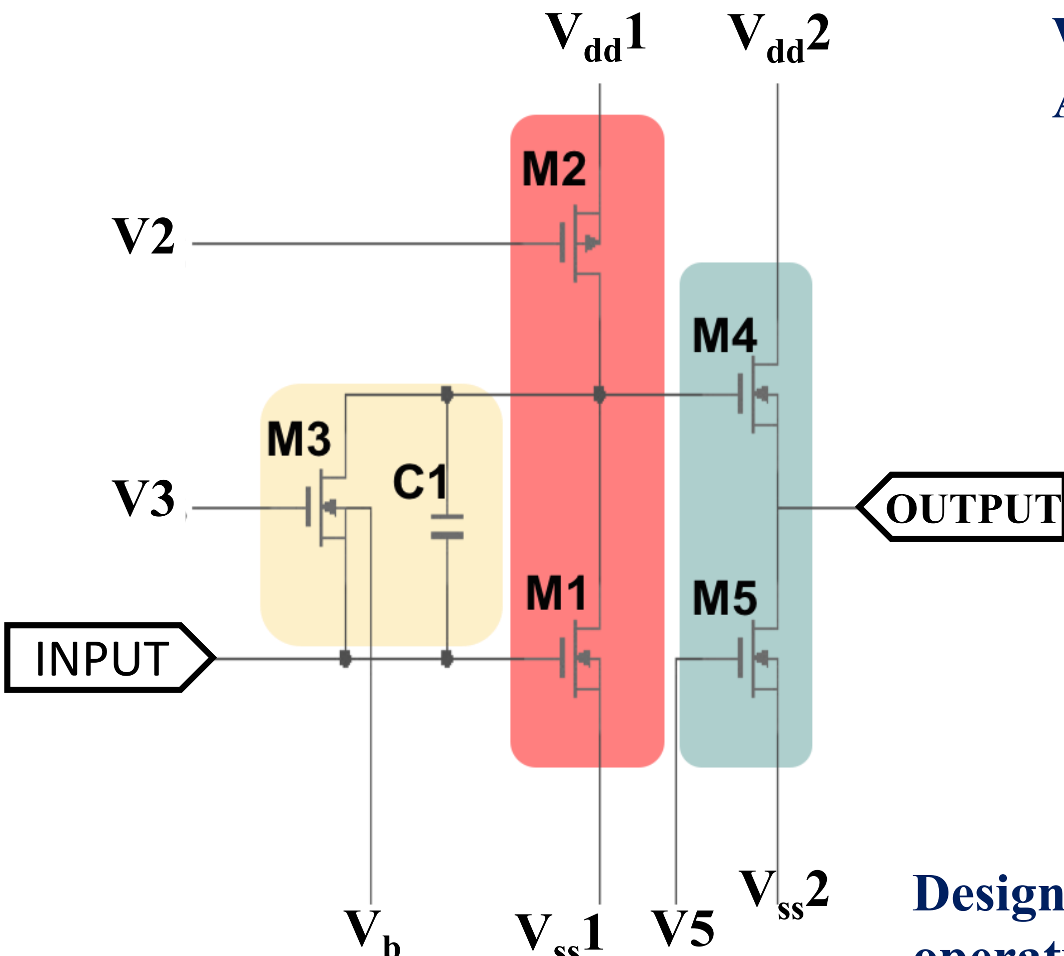




- We confirmed that the SOI-FET work as a preamplifier with a gain of 8.7 at 4K up to 100kHz.

SOI Cryogenic Amplifier

SOI-STJ4 (the 4th prototype)



We updated the SOI cryogenic Amplifier for Nb/Al-STJ.

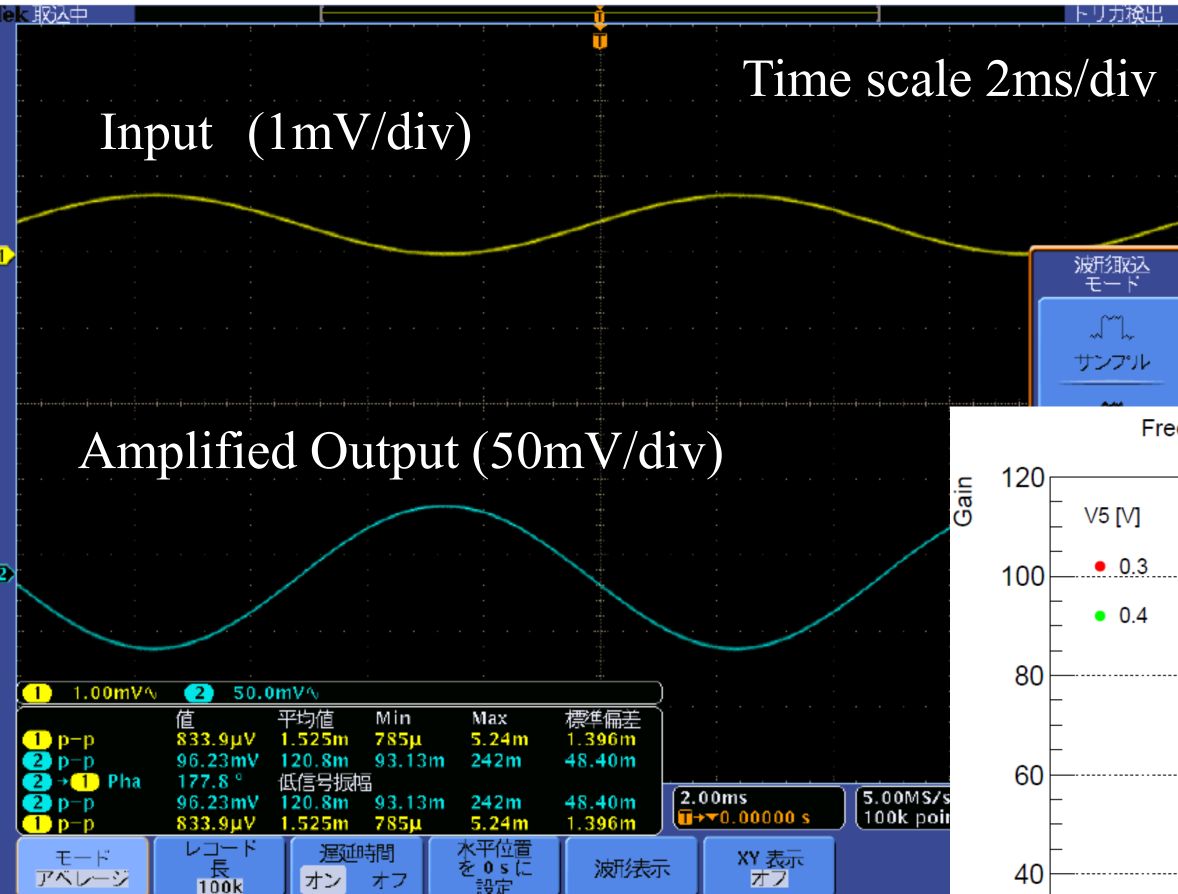
Amplification
Replace the resistance by a SOIFET as a current source (M2).
Feedback
Use the feedback between the drain and the gate of M1 to apply a stable bias voltage (M3).
Buffer
Add the follower to reduce the output impedance (M4 and M5).

Designed the ratio (W/L) to set the operation power consumption below 120μW.

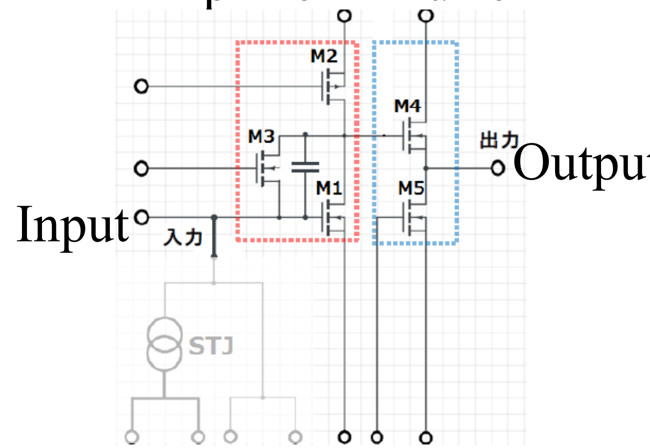
This SOI amplifier board was made by LAPIS semiconductor company.

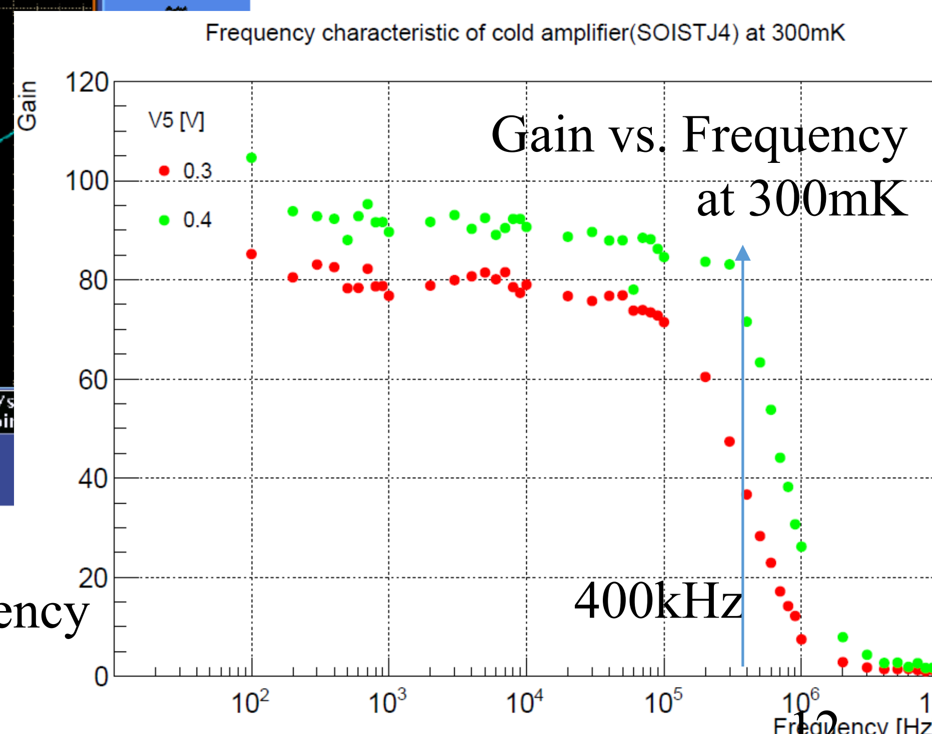
Test Results of the SOI Cryogenic Amplifier

Input and Amplified Output



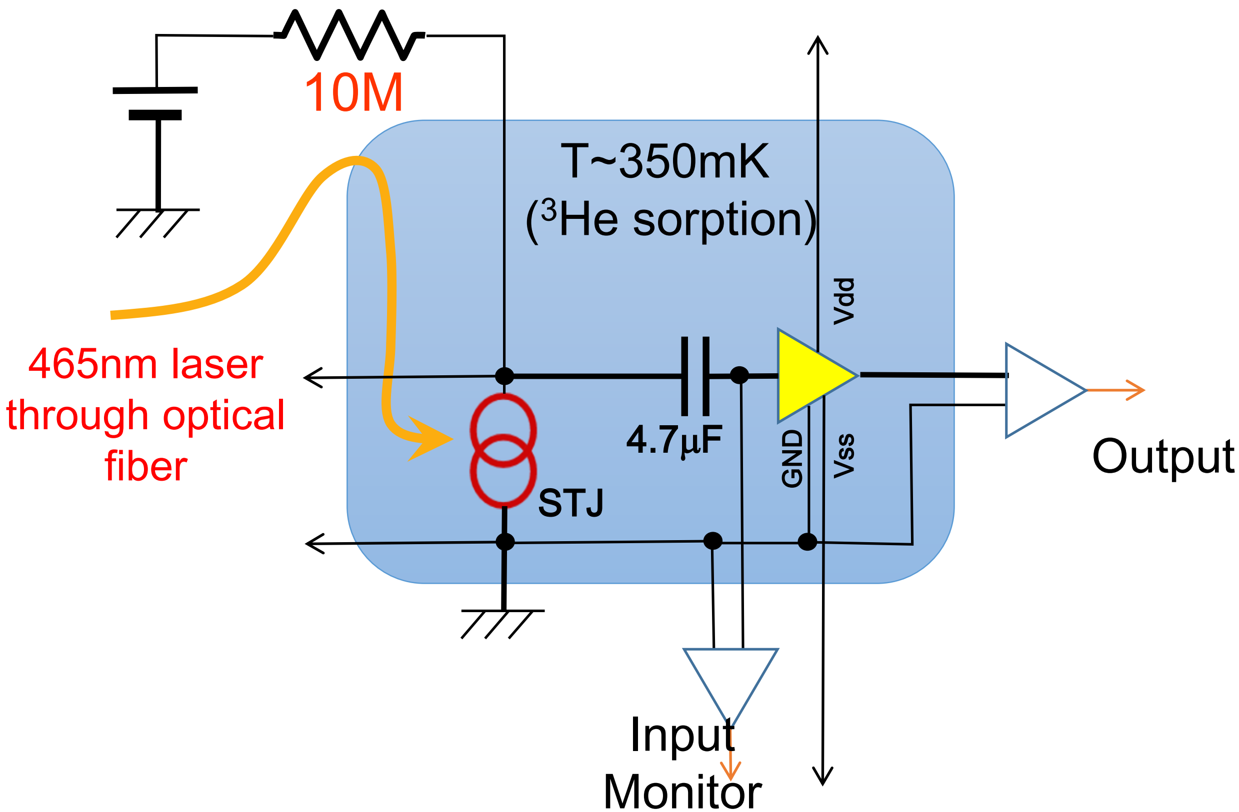
Amplifier + Buffer

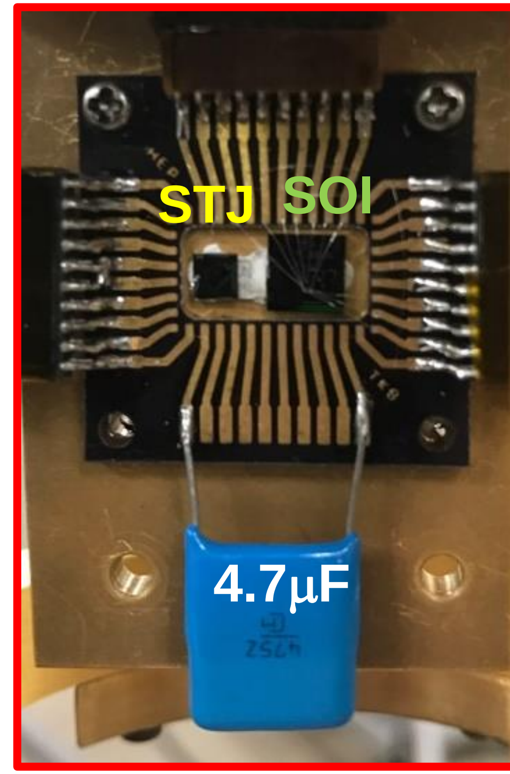




Gain of 80 was achieved for a signal frequency up to 400kHz signals at 300mK.

Setup of STJ Signal Amplification with the SOI Cryogenic Amplifier

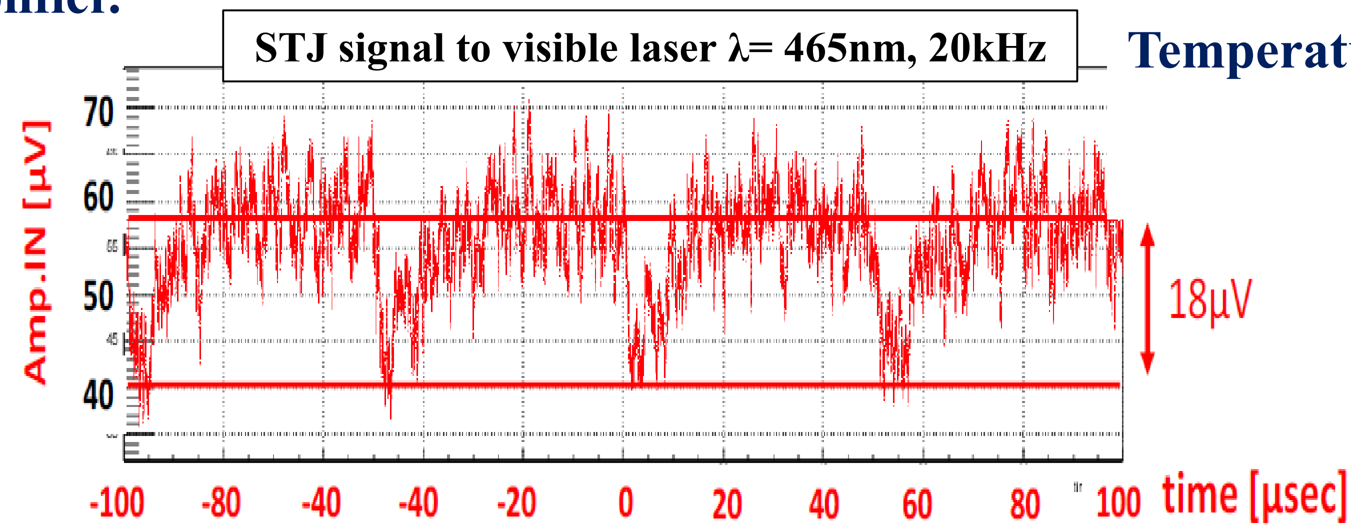




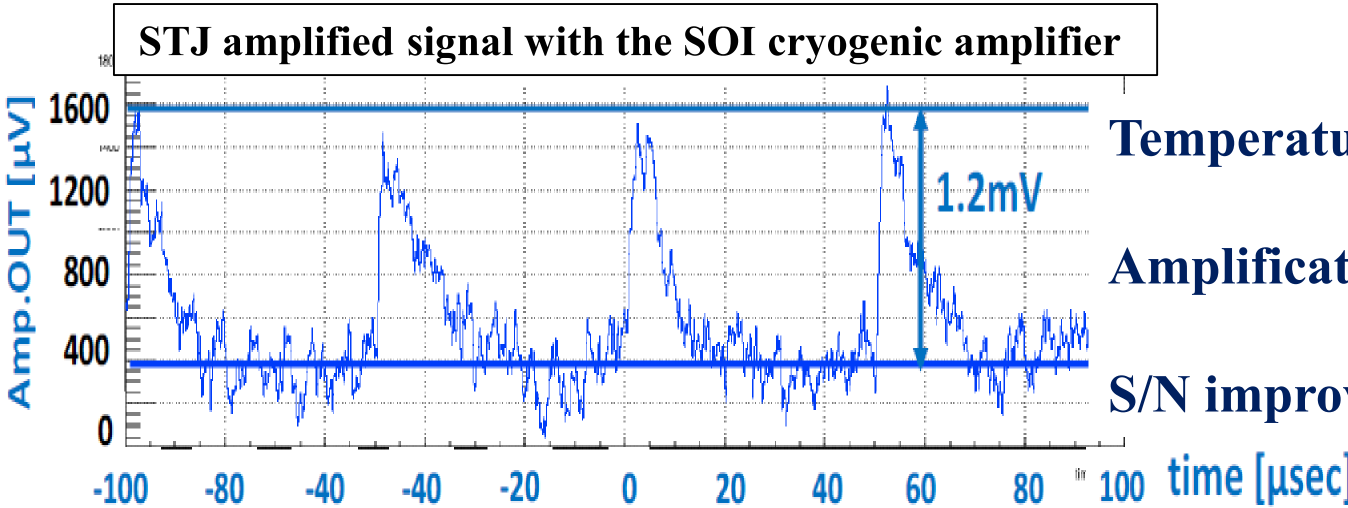
- **20μm-square Nb/Al-STJ with SOI-STJ4 amplifier through 4.7μF capacitance.**
- **Input impedance of the SOI amplifier is about 20kΩ.**
  - **STJ operation at a constant current mode.**
  - **STJ bias cable capacitance is around 1nF : Z=160Ω for 1μs signal.**

STJ signal amplified with the SOI cryogenic preamplifier

Nb/Al-STJ laser light response signal was amplified with this SOI cryogenic amplifier.



Temperature : 350mK



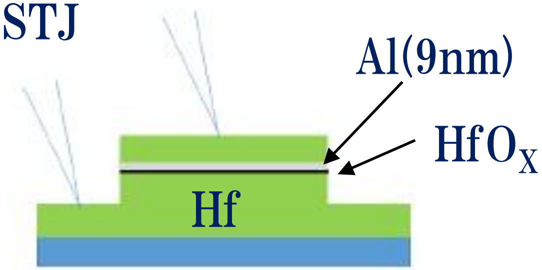
Temperature : 350mK

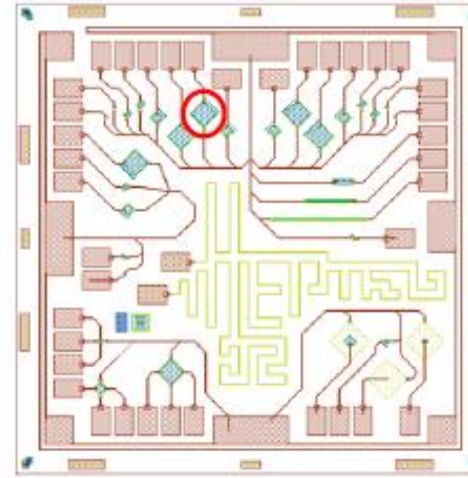
Amplification Gain : 70

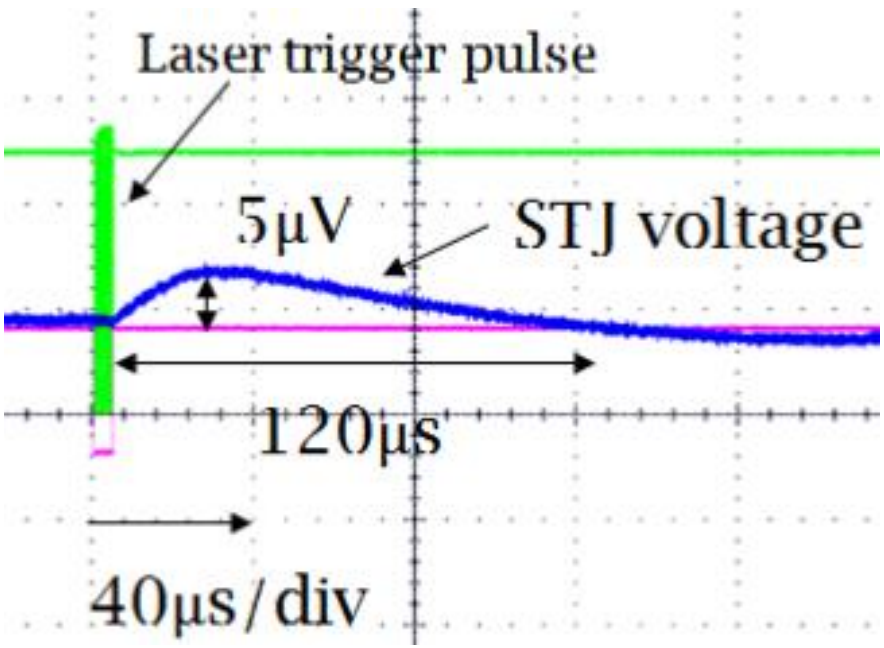
S/N improved by a factor of 2

Latest Results of Hf-STJ R&D

We made a thin aluminum layer (9nm) on the HfO layer (1-2 nm) to improve the insulation of the HfO_X layer. $Hf/Al/HfO_X/Hf$-STJ







Visible light laser (λ=465nm)   10Hz duration

Response speed (120μs) is slower than Nb/Al-STJ response speed (around a few μs).

More details of the Hf-STJ R&D results is presented in the poster session by K. Takemasa (P1-13).

Summary

- **R&D of STJ detectors and the design of the COBAND rocket experiment are underway.**
  - ➢ **Determination of the neutrino mass**
    - □ **origin of elementary particle mass spectra**
  - ➢ **Discovery of the cosmic background neutrino**
    - □ **new probe of the very early universe**

- **New far-infrared photon detector is being developed:**
  - ➢ **Nb/Al-STJ satisfied our requirement for leakage current less than 0.1nA**
  - ➢ **Cryogenic amplifier with the SOI technology worked at 300mK**

    We have succeeded in amplifying the STJ signal with the SOI cryogenic amplifier.
  - ➢ **Aiming at one photon detection in the far-infrared range**
  - ➢ **applicable to the other fields such as X-ray energy measurement with higher energy resolution.**

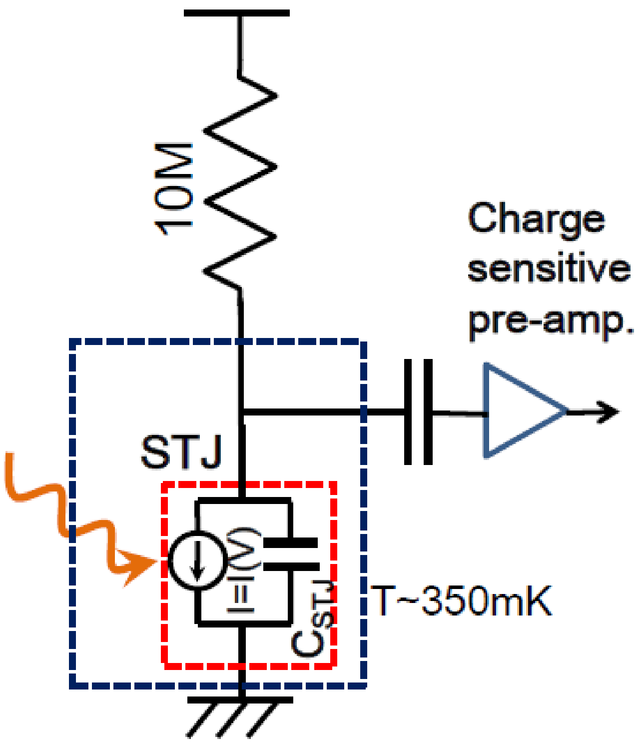
COBAND WEB page http://hep.px.tsukuba.ac.jp/coband/eng/

BACKUP

Development of SOI Charge sensitive preamplifier (SOI-STJ5)

- STJ capacitance is not so small (20pF for 20μm square STJ).
- STJ response speed is a few μsec.
- STJ operation at a constant voltage mode is favorable.

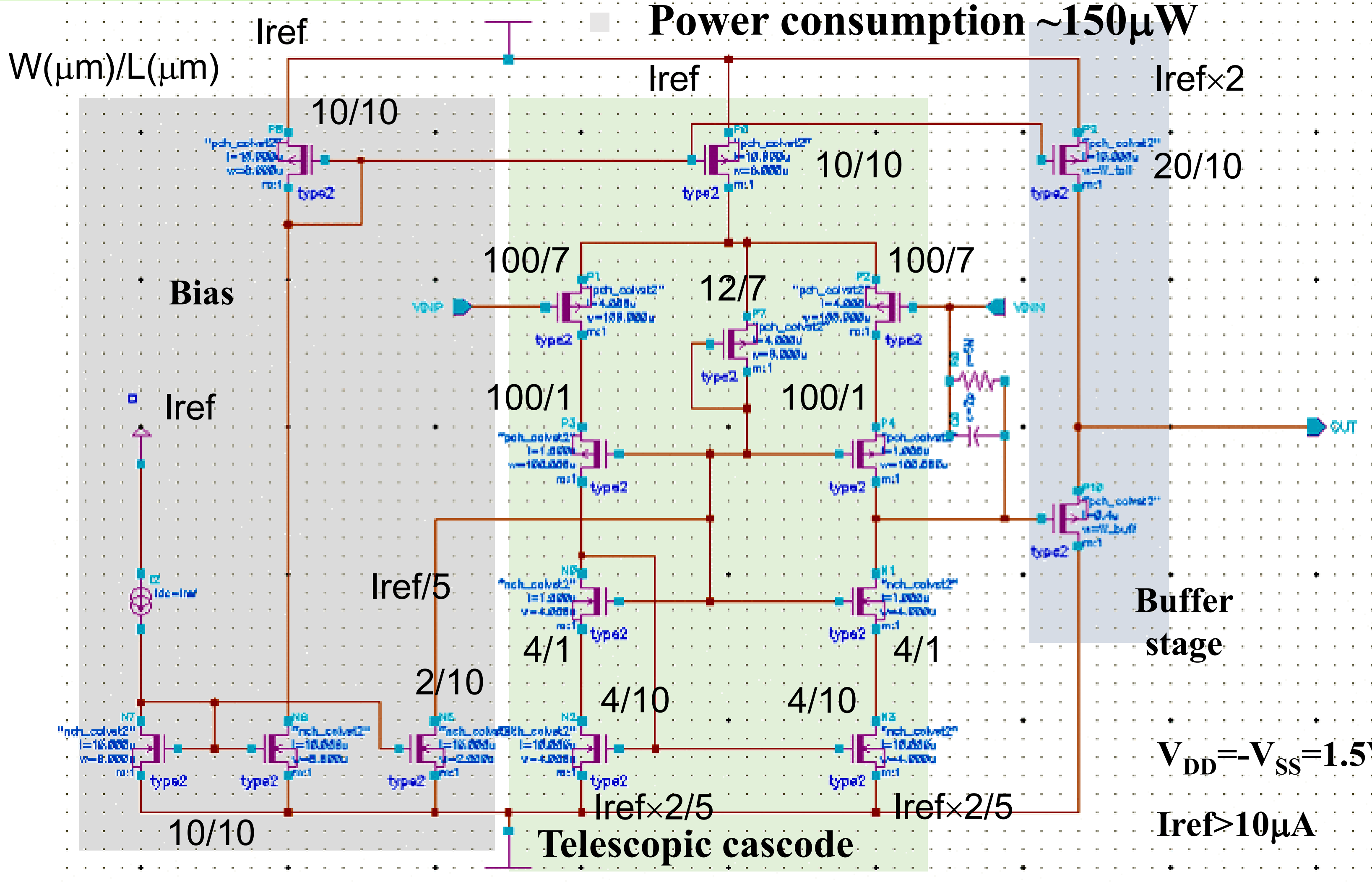
  → Low input impedance charge amplifier operational for 1MHz.



Op-amp Circuit for STJ (SOI-STJ5 design)

Test of this cryogenic charge amplifier is now underway.

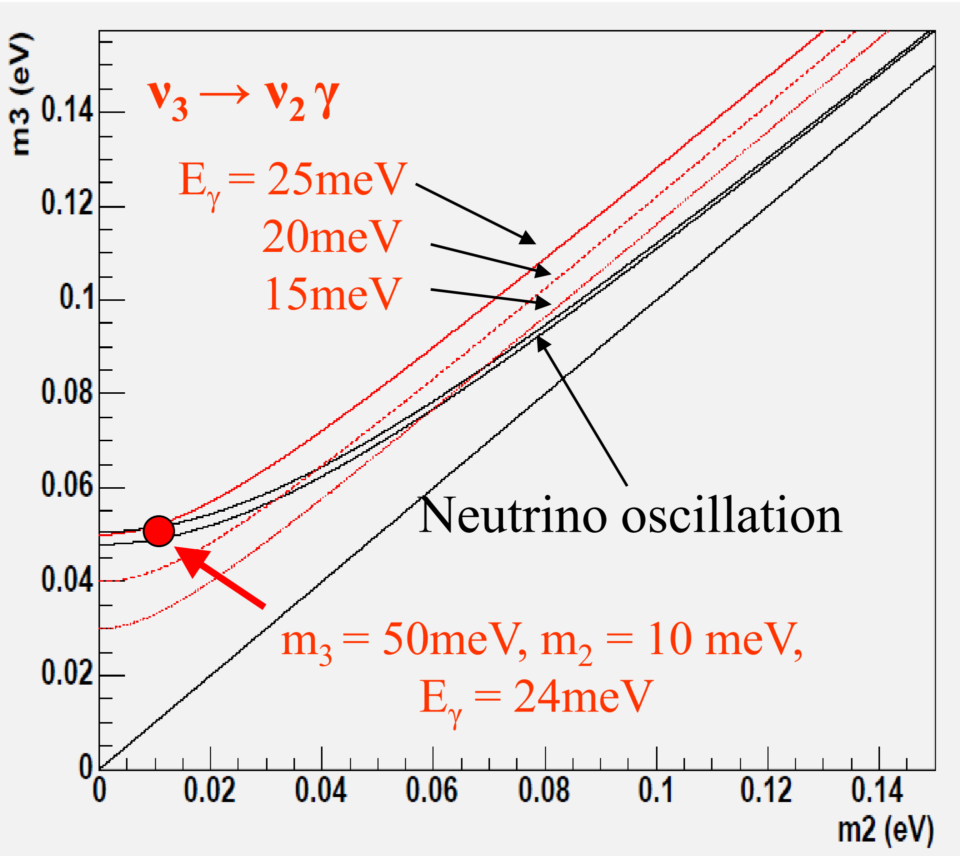
- telescopic cascode differential amplifier
- Feedback C=2pF x R=5MΩ = 10μs
- Power consumption ~150μW



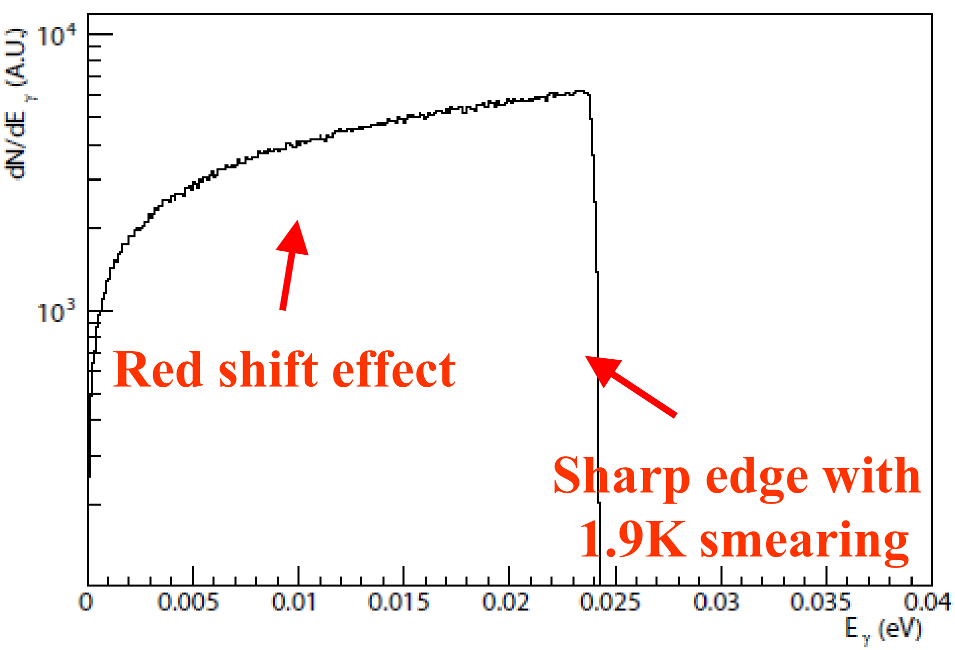
V_{DD}=-V_{SS}=1.5V

Iref>10μA

Neutrino Mass Relations
and Expected Photon Energy Spectrum



Decay Photon Energy Spectrum



Results from direct measuremenmt
(Tritium Decay)

$m(\nu_e) < 2\text{eV}$

$$\frac{dN}{dE_\gamma dS d\Omega dt} = \frac{\rho c}{4\pi\tau H_0 E_\gamma}\left[\left(\frac{E_{\gamma rest}}{E_\gamma}\right)^3 \Omega_M + \Omega_\Lambda\right]^{-\frac{1}{2}}$$

$E_{\gamma rest}$: photon energy in ν_3 rest frame, ρ : ν_3 density, τ : ν_3 lifetime,

H_0 : Hubble constant, Ω_M : Matter density (0.76), Ω_Λ : cosmological constant (0.24)

Zodiacal Emission

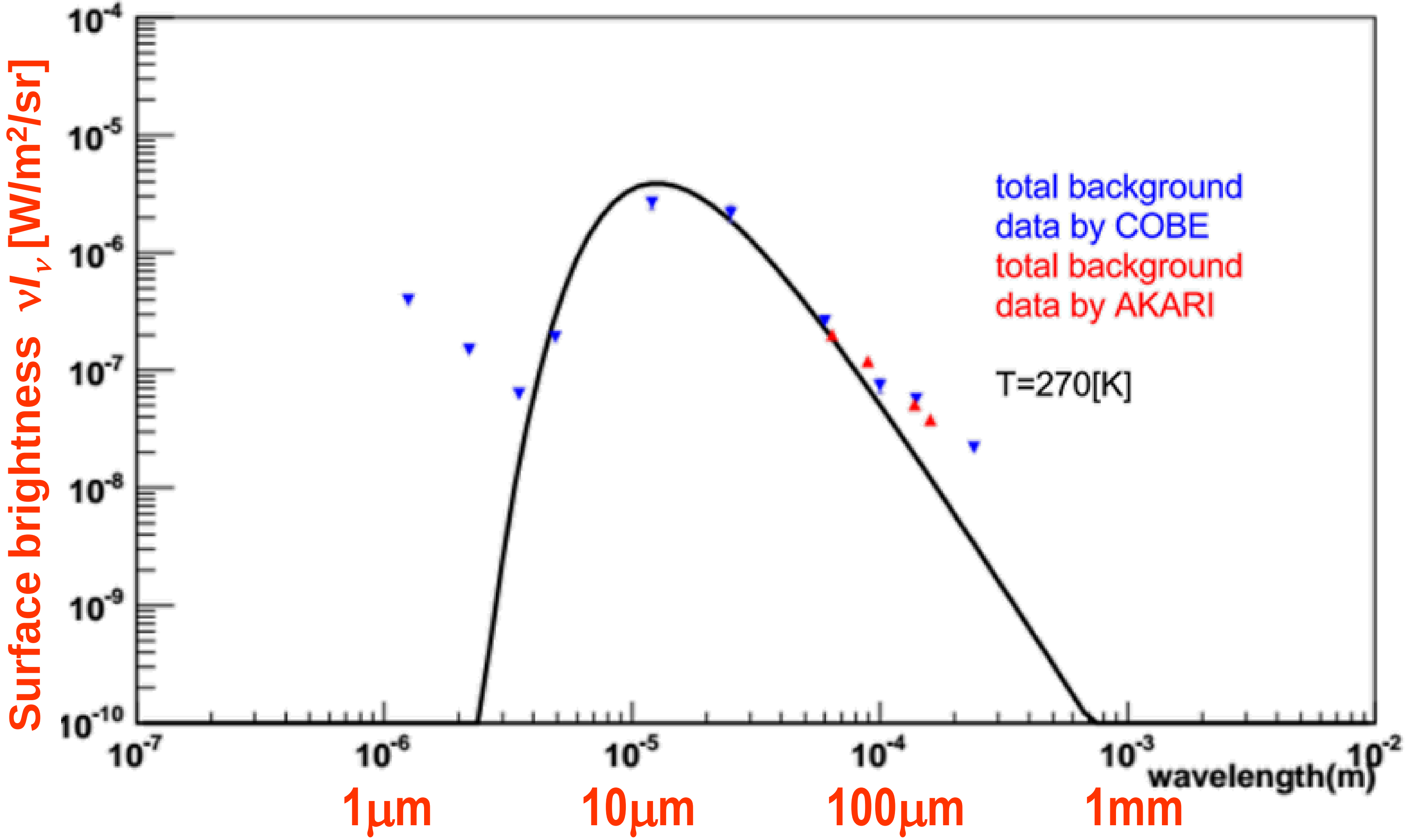
Thermal emission from the interplanetary dust cloud

$$I_\nu = \frac{2h\nu^3}{c^2}\frac{1}{\exp(h\nu/kT) - 1} \times A\left(\frac{\nu}{c} \times 10^{-5}\right)^B \ \mathrm{Wm^{-2}sr^{-1}}$$

- $T = 270K$, $A = 6 \times 10^{-8}$, $B = 0.3$
- h [Js], c [m/s], λ [m]

Zodiacal Emission(ZE) is overwhelmingly dominating. Here we consider only ZE as the background.

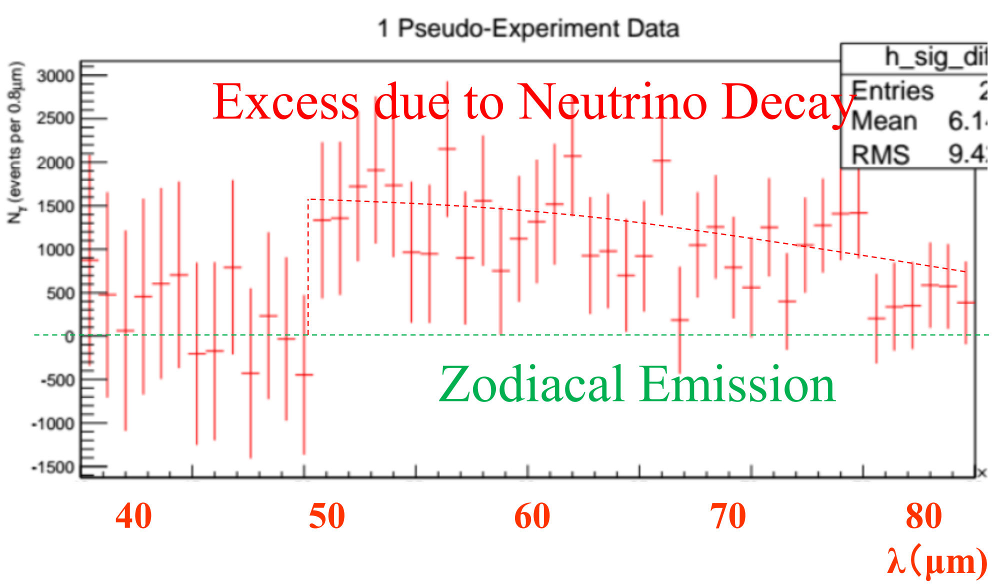
Zodiacal Emission

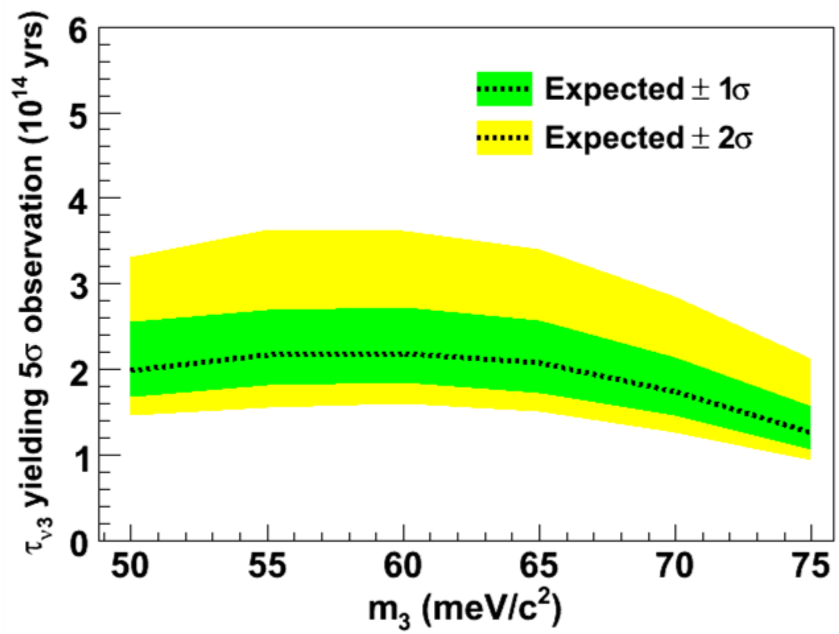


Sensitivity to neutrino decay

Parameters in the rocket experiment simulation

- telescope dia.: 15cm
- 50-column (λ: 40μm – 80 μm) $\times$ 8-row array
- Viewing angle per single pixel: 100μrad $\times$ 100μrad
- Measurement time: 200 sec.
- Photon detection efficiency: 100%





- If ν_3 lifetime were 2×10^{14} yrs, the signal significance is at 5σ level

STJ Energy Resolution

STJ Energy Resolution

$$\sigma_E = \sqrt{1.7\Delta(FE)}$$

Using Hf as a superconductor,

$$\sigma_E / E = 1.7\% \quad \text{at } E = 25\text{meV}$$

Δ: Band gap energy
F: Fano factor (= 0.2)
E: Incident particle energy

Material	$T_c(K)$	$\Delta(\text{meV})$
Niobium	9.20	1.550
Aluminum	1.14	0.172
Hafnium	0.13	0.021

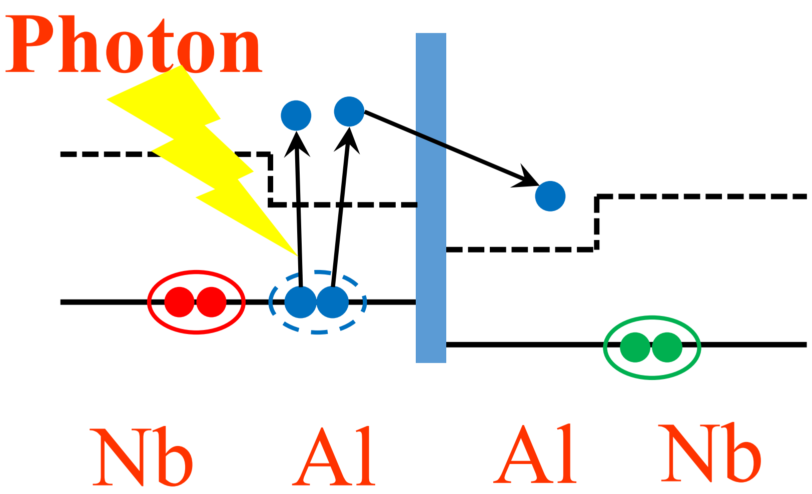
Tc : Critical Temperature

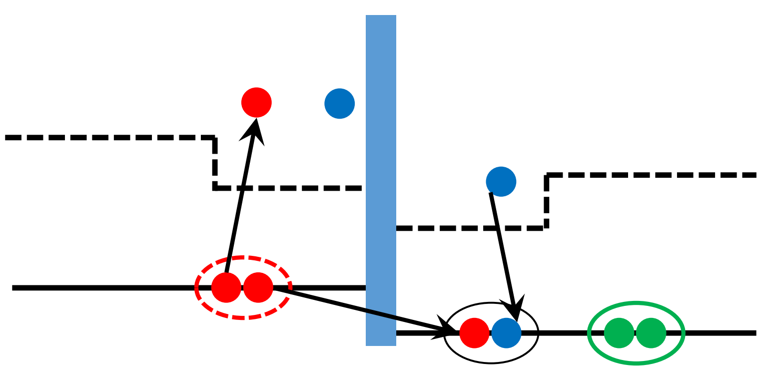
Operation is done at a temperature around 1/10 of Tc

We reported that Hf-STJ worked as a STJ in TIPP2011.

STJ back tunneling effect

- Quasi-particles near the barrier can mediate Cooper pairs, resulting in true signal gain
  - Bi-layer fabricated with superconductors of different gaps $\Delta_{Nb} > \Delta_{Al}$ to enhance quasi-particle density near the barrier
  - Nb/Al-STJ   Nb(200nm)/Al(10nm)/AlOx/Al(10nm)/Nb(100nm)
- Gain: 2〜200





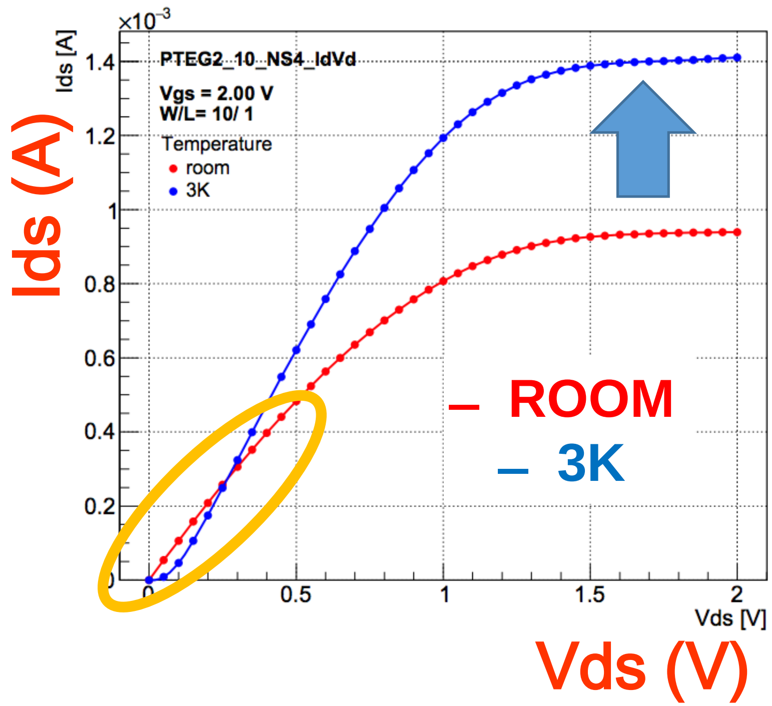
Performance of SOIFET at Cryogenic Temperature

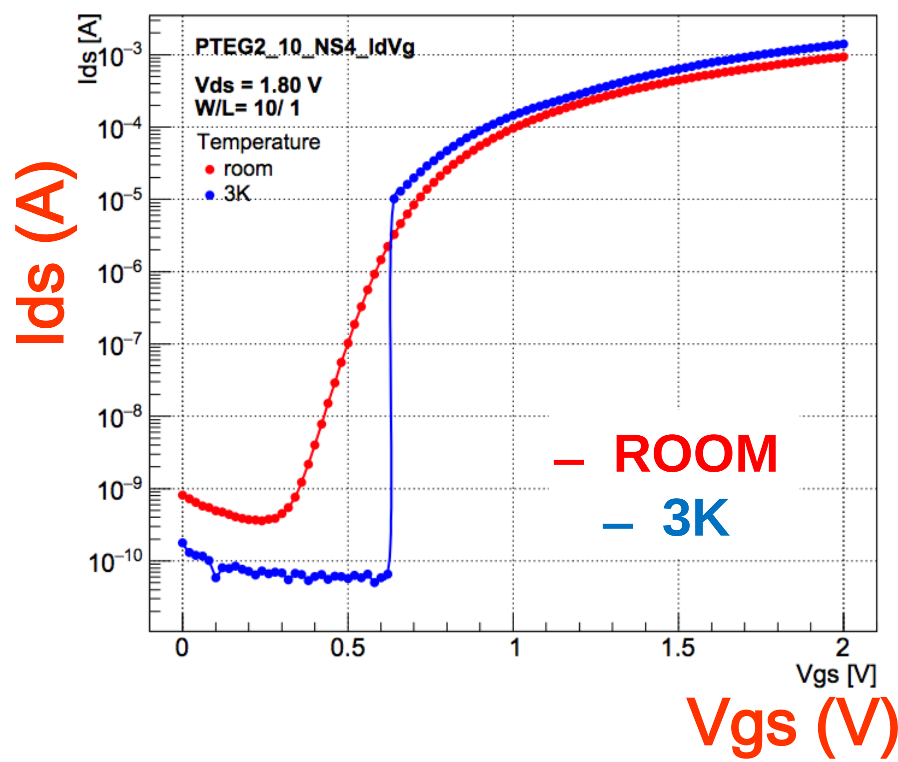
Saturating current is higher as the temperature becomes lower.

Non-linearity was found at cryogenic temperature near threshold region. This problem was solved by improving LDD(Lightly Doped Drain).

At cryogenic temperature (3K),

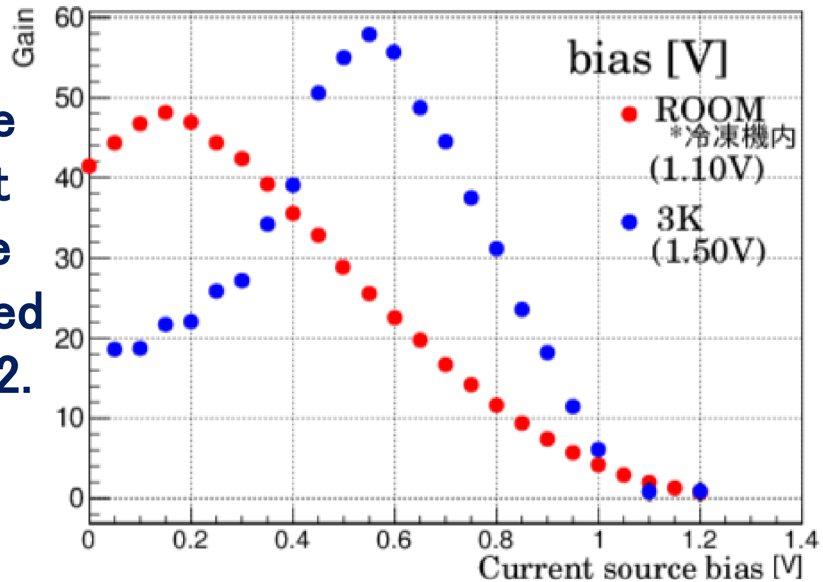
- **Threshold rise in I_{ds}-V_{ds} curve become much sharper.**
- **Subthreshold current is suppressed.**

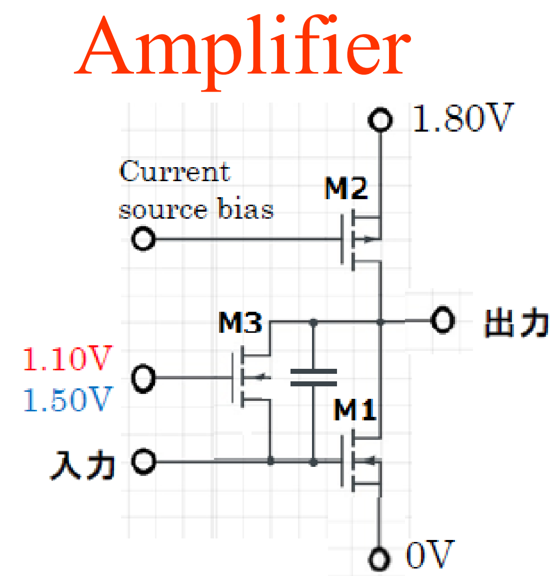




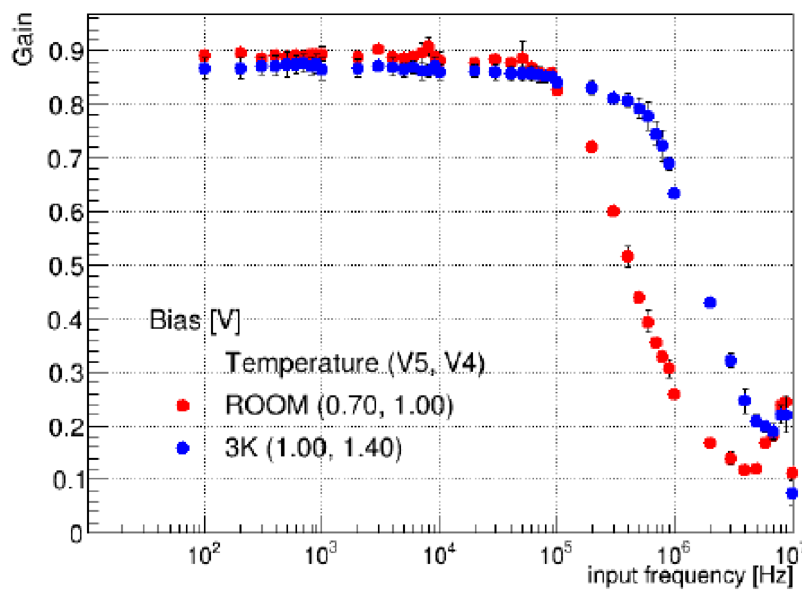
Test Results of the cryogenic SOI preamplifier

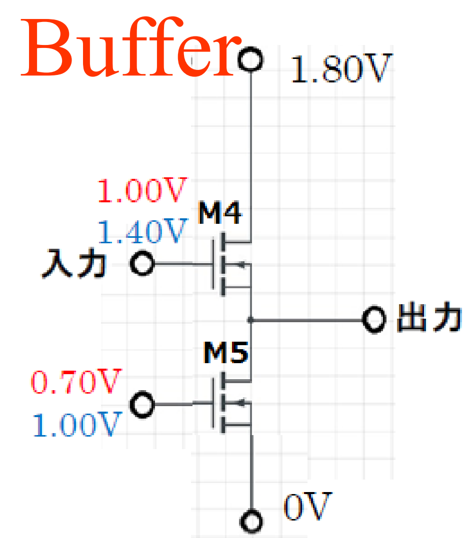
Amplifier gains are around 50 both at room temperature and 3K with adjusted bias voltages of M2.



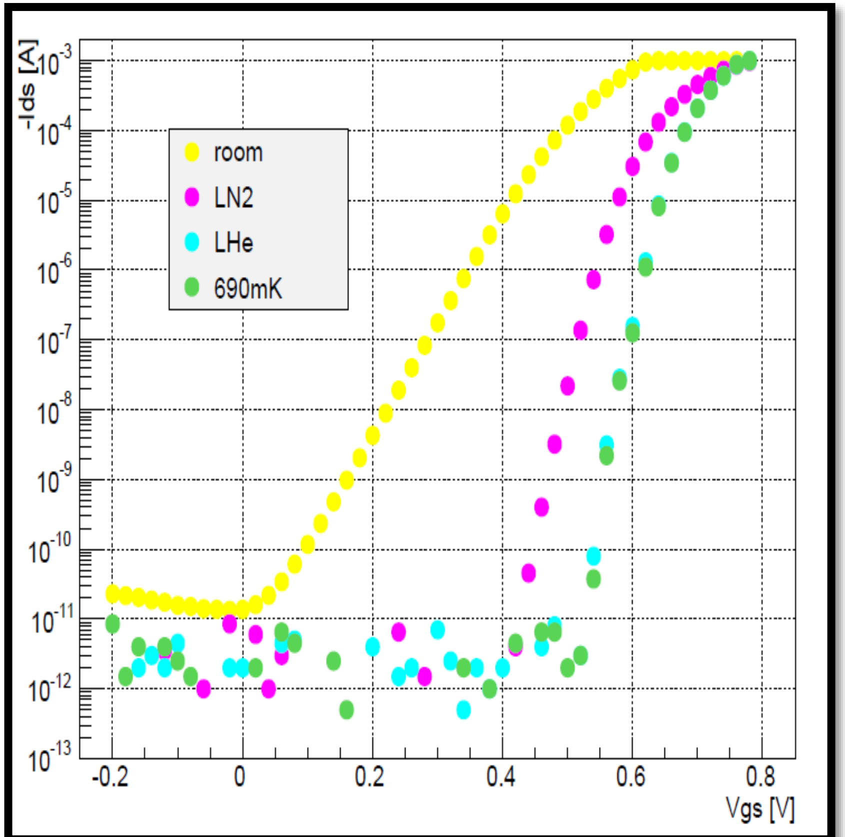


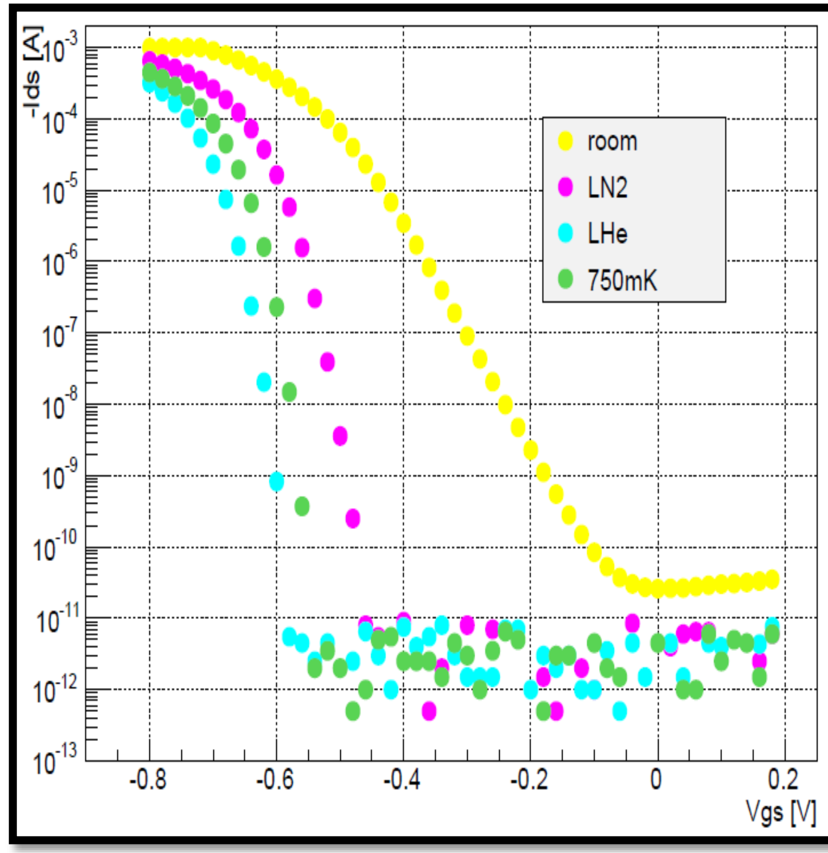
Bandwidth of buffer is enough high for the amplifier of STJ signal (up to 200kHz) both at room temperature and 3K.





Temperature Dependence of I-V curve



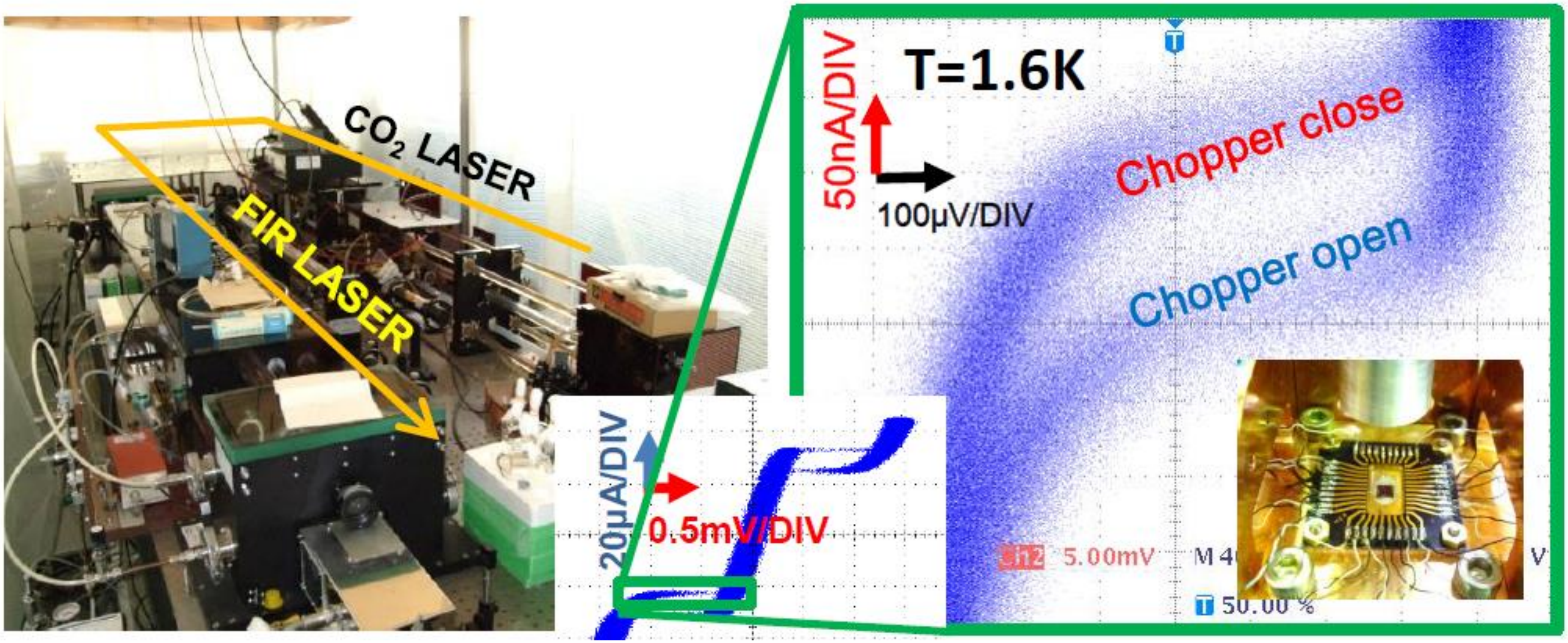


Threshold voltage is changed. But the other properties are almost unchanged.

Test Results of Nb/Al-STJ with Far-Infrared laser

Far-Infrared Laser at University of Fukui
(λ=57.2μm)

- Nb/Al-STJ Response to Far-Infrared Laser



- 20μm-square Nb/Al-STJ made at AIST CRAVITY system
- Laser light was turned on and off with a chopper at a frequency of 200Hz. Measured the change of the I-V curve between the laser on and off to be 50~100nA in current.