Development of STJ detector for cosmic background neutrino decay search

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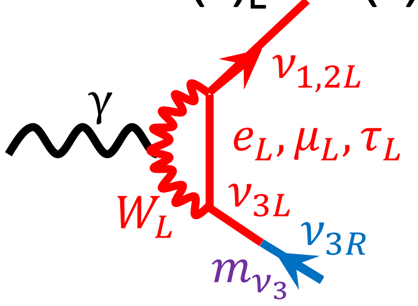
Motivation

- Only neutrino mass is unknown in elementary particles.
- Difference between mass-squared of different generation neutrino has been measured by various experiment of neutrino oscillation.
- Detection of neutrino radiative decay enables us to measure an independent quantity of Δm^2.
- $\rightarrow$ We can obtain neutrino mass itself from these two independent measurements.

Neutrino radiative decay

- In neutrino decay process, a lighter neutrino and a photon are emitted from a heavier neutrino.
  - $\nu_3 \rightarrow \nu_2 + \gamma$
- In the standard model, the heaviest neutrino lifetime is predicted to be 10^{43} year for ν_3 with a mass of $50 meV/c^2$.
- In the Left–Right symmetric model, lifetime is calculated to be 1.5×10^{17} year.
- Measured neutrino lifetime limit: $\tau > 3 \times 10^{12}$ years (AKARI).

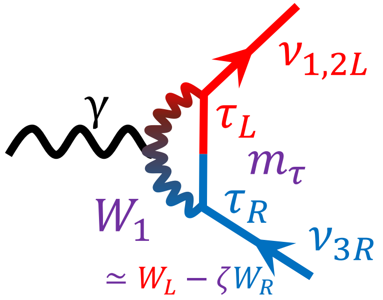
SM: $SU(2)_L \times U(1)_Y$



$\Gamma \sim (10^{43}\ yr)^{-1}$

Suppressed by m_ν, GIM

LRS: $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$



$\Gamma \sim (10^{17}\ yr)^{-1}$

Suppressed only by $\zeta \sim 0.02$

PRL 38,(1977)1252, PRD 17(1978)1395

$$\begin{pmatrix} W_1 \\ W_2 \end{pmatrix} = \begin{pmatrix} \cos\zeta & -\sin\zeta \\ \sin\zeta & \cos\zeta \end{pmatrix} \begin{pmatrix} W_L \\ W_R \end{pmatrix}$$

10^{26} enhancement to SM

Energy spectrum of neutrino decay

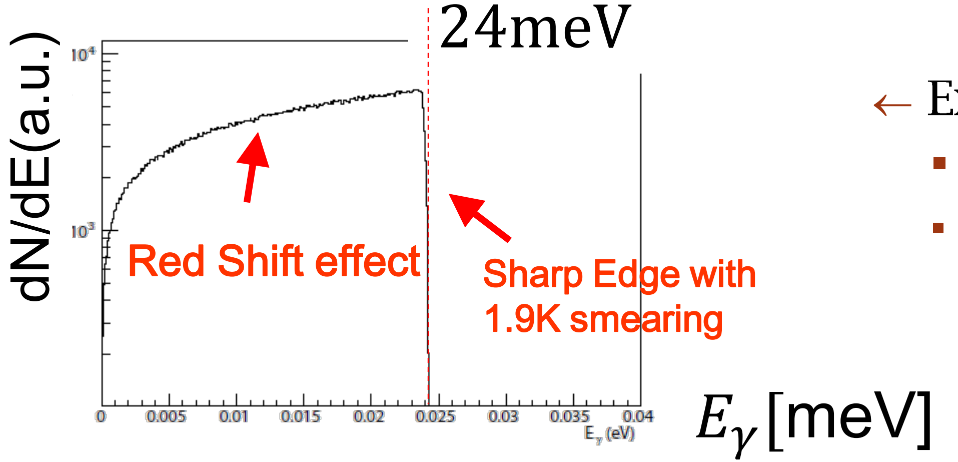
- Energy of the photon:

$$E_\gamma = \frac{m_3^2 - m_{1,2}^2}{2m_3}$$

- From neutrino oscillation
  - $\Delta m_{23}^2 = |m_3^2 - m_2^2| = 2.4 \times 10^{-3}\ eV^2$
  - $\Delta m_{12}^2 = 7.65 \times 10^{-5}\ eV^2$
- From Planck+WP+highL+BAO
  - $\sum m_i < 0.23$ eV

➔ 50meV< m_3 <87meV,
E_γ =14~24meV
λ_γ =51~89µm

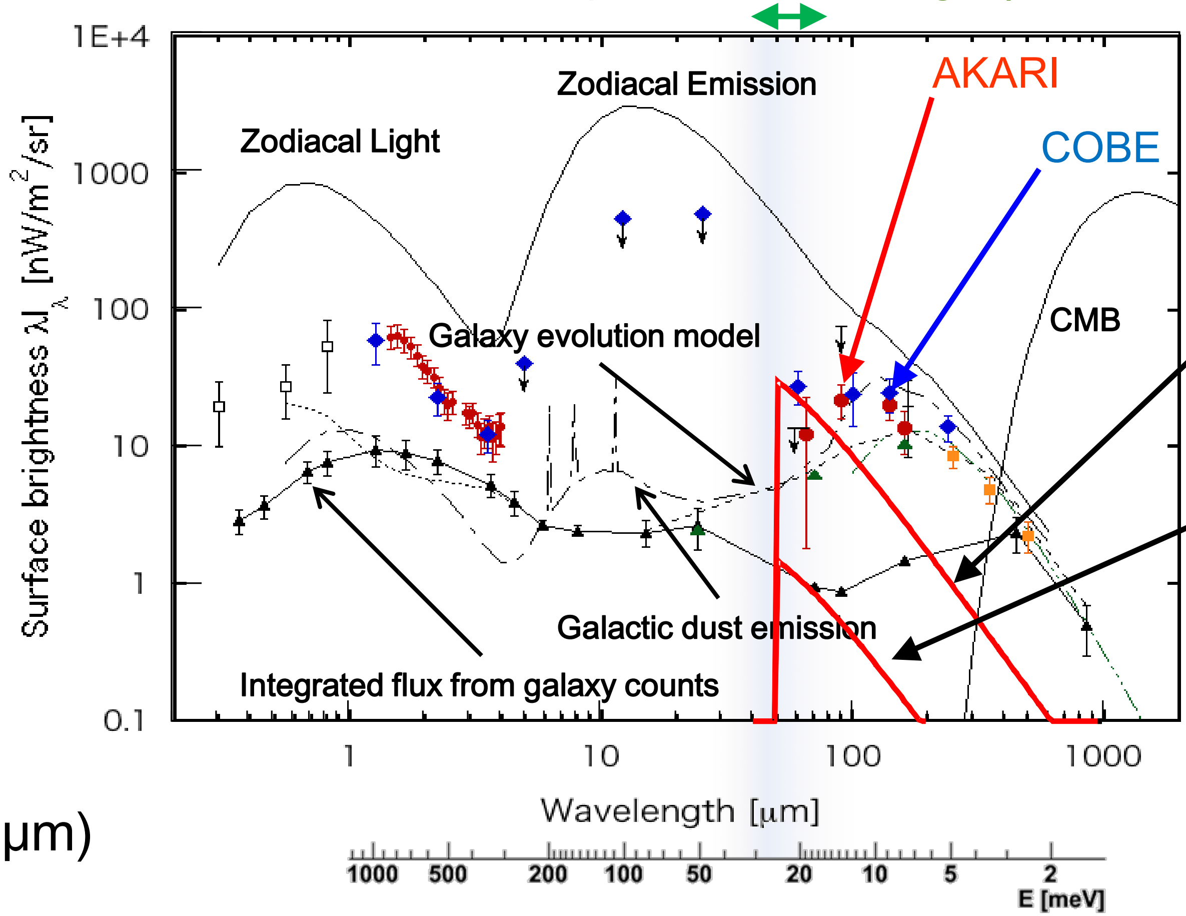
- As τ_ν is so long, to observe ν decay, we need immense quantity of neutrino.
- Most promising method is to observe the decay of cosmic background neutrino(CBN).
  - CBN has a temperature of 1.9K and a particle density ρ of 110 cm^{-3} per generation.
- Energy spectrum of the photon from CBN decay has a cutoff at this energy and a low energy tail due to a red shift effect.



← Expected energy spectrum of CBN decay($\nu_3 \rightarrow \nu_2 + \gamma$)
- m_3 = 50meV is assumed
- Eγ at neutrino rest frame = 25meV

Signal of CBN decay and it's background

Rocket experiment coverage (λ = 40 ~ 80μm)



Background

Zodiacal Emission
λI_λ~500nW/m²/sr

CIB (COBE)
λI_λ~30nW/m²/s

at $E_\gamma = 25\text{meV}$ (λ = 50μm)

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

ν-decay ($\tau = 5 \times 10^{12}\text{yr}$)
λI_λ~30nW/m²/s

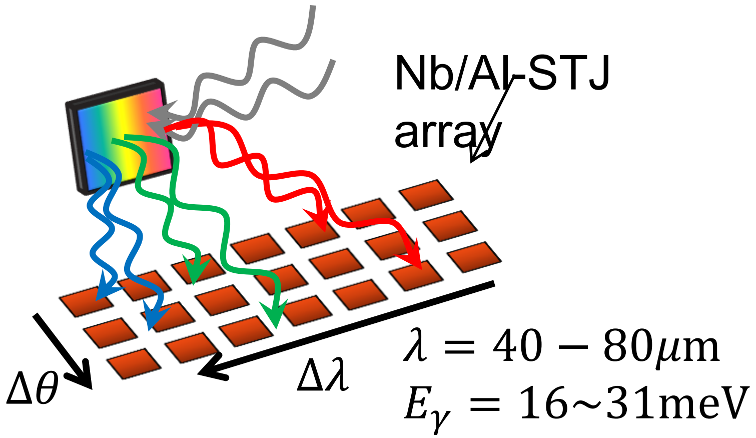
ν-decay ($\tau = 1 \times 10^{14}\text{yr}$)
λI_λ~1.5nW/m²/s

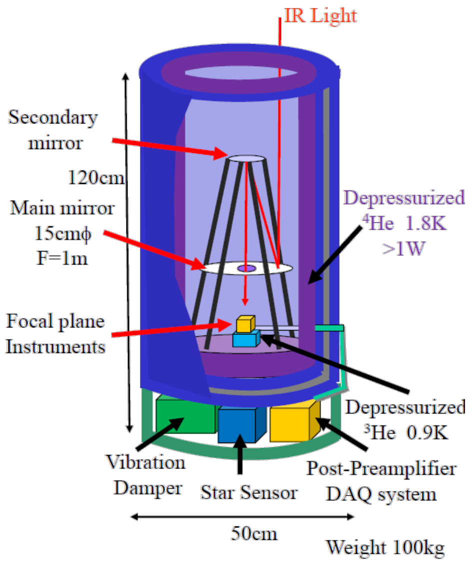
ν-decay ($\tau = 1 \times 10^{17}\text{yr}$)
λI_λ~1.5pW/m²/s

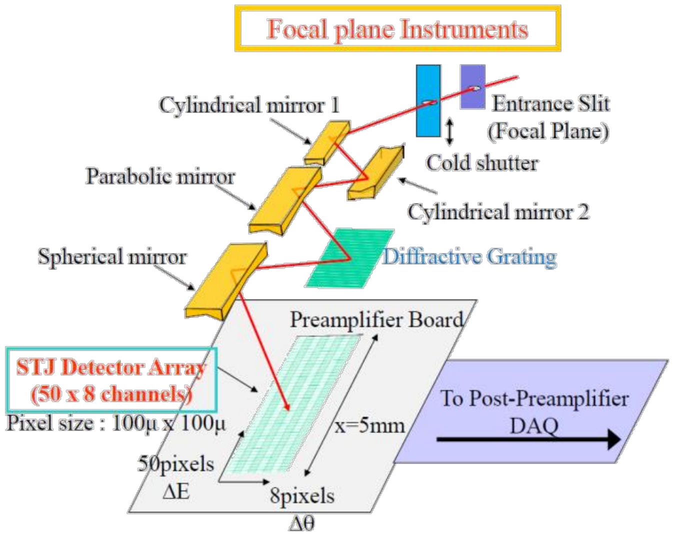
By measuring the energy spectrum of the Zodiacal Emission with the CBN decay continuously, we can see the CBN decay signal as a high energy cutoff.
To identify the shape edge, we need detector which has better than 2% resolution for Eγ ~ 25meV

Rocket/satellite experiment

- **Rocket experiment**
  - 200sec data acquisition at 200 km height in 2017 in earliest.
  - Improve the current limit of lifetime τ(ν3) by two orders of magnitude (~10^{14}years).
  - Detector: Array of 50 Nb/Al-STJ pixels with diffraction grating covering $\boldsymbol{\lambda = 40 - 80\mu m}$
    Nb/Al-STJ has poor resolution for identify signal cutoff, but counting is possible.







- **Satellite experiment after 2020**
  - Expected sensitivity: τ(ν3) ~ 10^{17}year
  - Detector: STJ detector using Hafnium(Hf-STJ)
    Hf-STJ achieves 2% energy resolution if fano factor <0.3

Detector requirement for CBN decay search

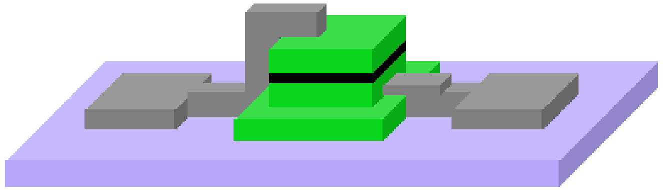
- Detector requirements
  - Continuous spectrum of photon energy around $E\gamma \sim 25$meV($\lambda=50\mu$m, far infrared photon)
  - Energy measurement for single photon with better than 2% resolution for $E\gamma \sim 25$meV to identify the shape edge in the spectrum.
  - Rocket and/or satellite experiment with this detector.

- STJ detector is able to achieve these requirements.

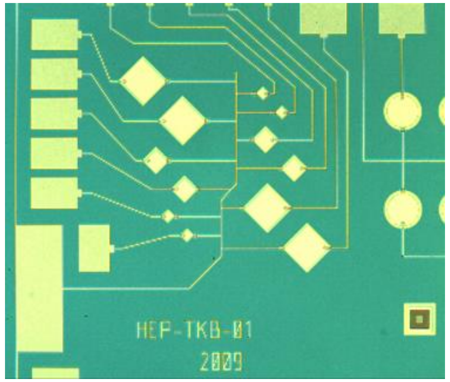
  We are developing two types of STJ detector.
  - Nb/Al-STJ
    - For rocket experiment aiming at launching in two years after the detector R&D completion (in 2017 in earliest), expecting improvement of current lower limit for $\tau(\nu_3)$ by 2 order:$O(10^{14}$year)
  - Hf-STJ
    - $\Delta=20\mu$eV:superconducting gap energy for hafnium
    - $N_{q.p.}=25\text{meV}/1.7\Delta = 735$ for 25meV photon: $\Delta E/E<2\%$ if fano-factor is less than 0.3

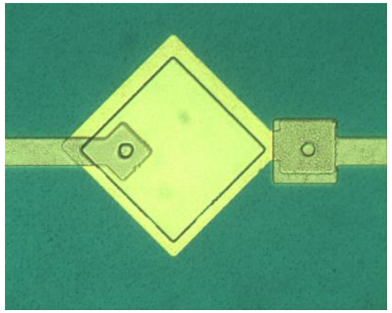
STJ (Superconducting Tunnel Junction) Detector

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

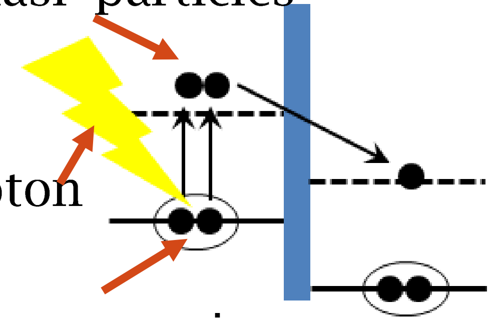


Overhead view of STJ detector





- **Working principle**
  - Incident photon is absorbed in the superconductor and excites cooper pairs.
  - Excited cooper pairs become quasi-particles.
  - Quasi-particles go through tunnel barrier 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 number of quasi-particles determines STJ energy resolution.
- Smaller superconducting gap energy Δ yields better energy resolution.

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

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	0.13	0.021

Tc : Superconducting critical temperature
Need ~1/10Tc for practical operation

Nb

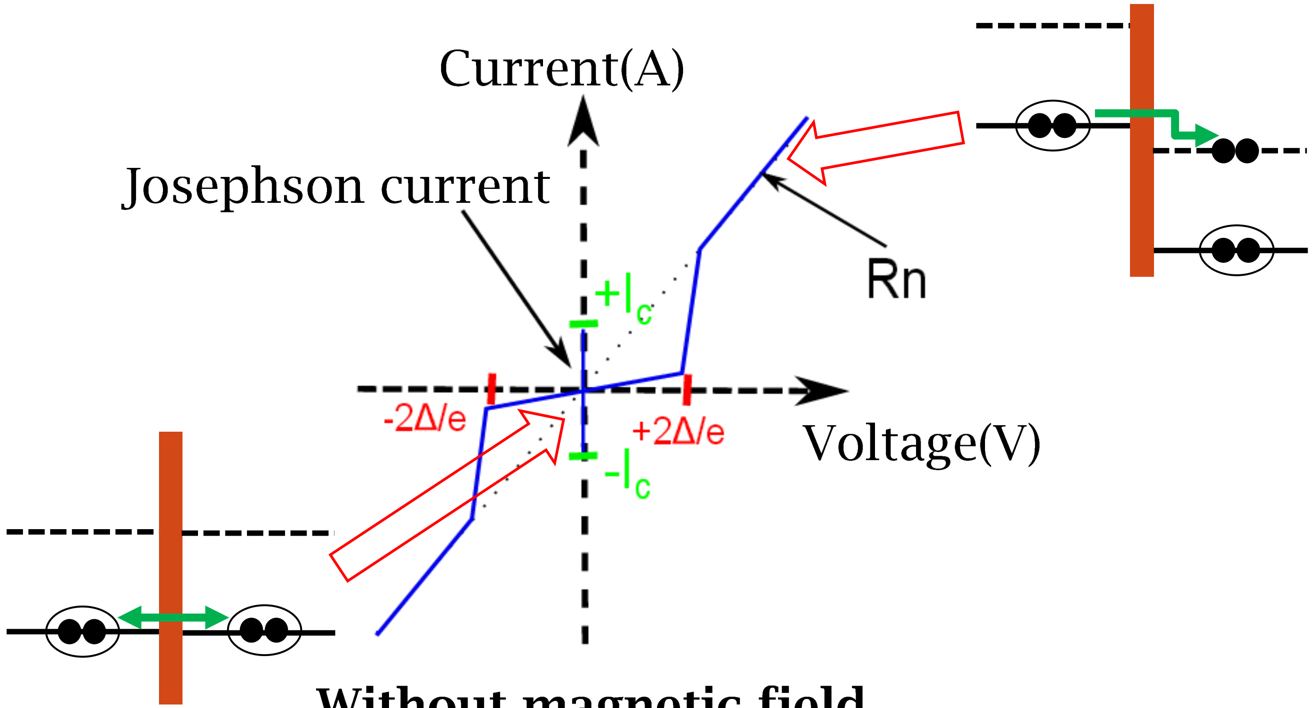
- Well established as Nb/Al-STJ
- $N_{q.p.} = 25\text{meV}/1.7\Delta = 9.5$
- poor resolution but counting is possible

Hf

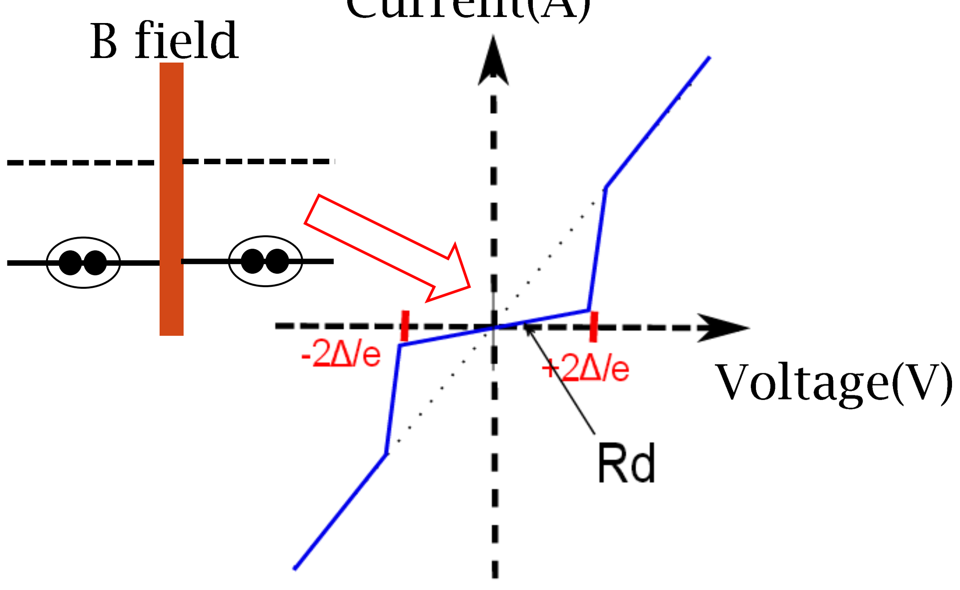
- Hf-STJ as a photon detector is not established
- $N_{q.p.} = 25\text{meV}/1.7\Delta = 735$
- 2% energy resolution is achievable if fano factor <0.3

IV curve of STJ detector

- The cooper pair tunneling current is seen at V=0, and the quasi-particle tunneling current is seen for |V| >2Δ.
- For detecting photons, STJ detector is operated with magnetic field of 10-100G.
- Josephson current is suppressed and change of quasi-particle tunnel current from incident particle can be measured.



Without magnetic field



With magnetic field

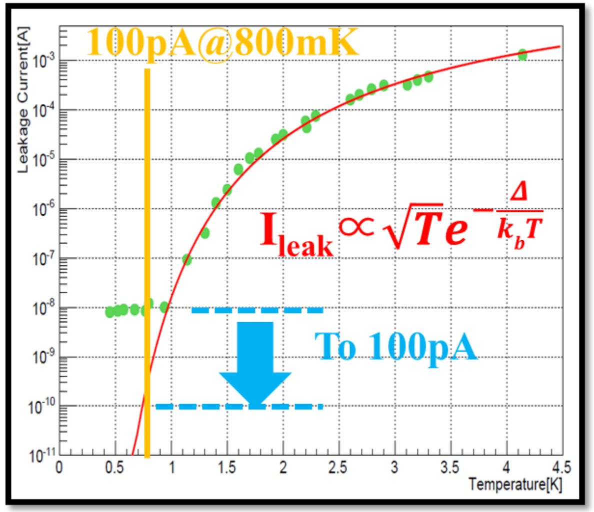
Current status of development of Nb/Al-STJ

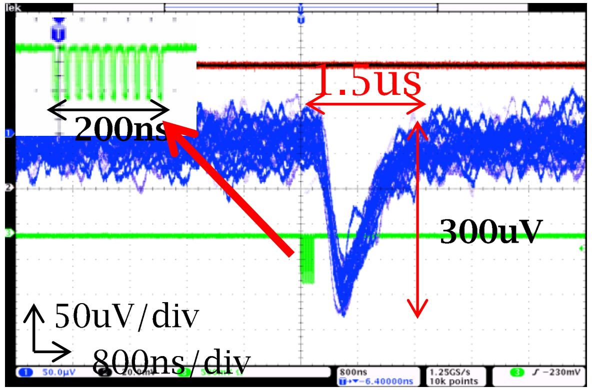
- Goal: detection of a single far-infrared photon in the energy range of 15-30meV(λ=40-80μm) for the rocket experiment for neutrino decay search.

Performance of our best Nb/Al-STJ sample

- **Leakage current**
  - Requirement: $I_{leak} < 100pA$
  - Measured: $I_{leak} \sim 10nA$ @ T<1K
  - To reduce I_{leak} :
    - Down sizing (I_{leak} depends on detector size)
    - cool down ~800mK (reduce thermal noise)
- **Frequency response**
  - Requirement: faster than 400Hz = 2.5ms
  - Measured: Time spread at FWHM is 1us.

Temperature Dependence of Leakage Current with Nb/Al-STJ(100x100μm^2)





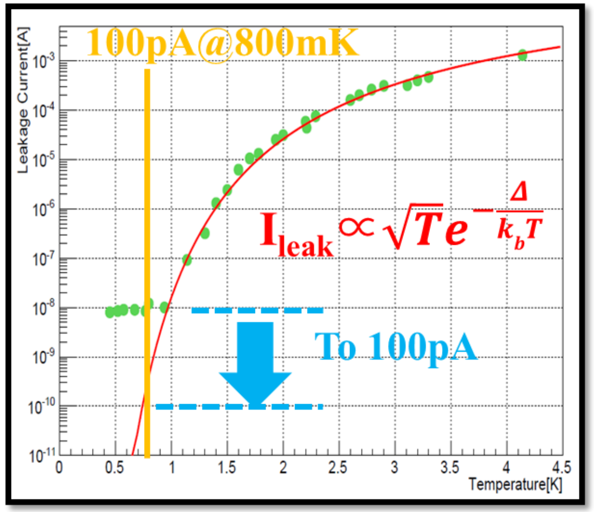
Signal shape(1.31um, N(photon)=91±11)

Requirement for cold amplifier

- We haven't succeeded in detecting a far infrared single photon due to read out noise.
- To improve the signal–to–noise ratio, we are developing cold amplifier.

- Requirement for cold amplifier
  - **Operation at ultra low temperature**
    - Requirement for leakage current of Nb/Al–STJ is below 100pA
    - To reduce thermal excitation($\propto \sqrt{T}\, e^{(-\Delta/kbT)}$), we need to make cooler 800mK.
    - Cold amplifier should be able to operate at 800mK.
  - **Low power consumption**
    - Typical cooling power of our refrigerator is 400μW.
    - Power consumption of the amplifier should be as low as possible.
  - **Response speed**
    - The integration time of charge is 2–4μs.
    - Amplification gain should be large enough up to 1MHz.

Temperature Dependence of Leakage Current with Nb/Al-STJ(100x100μm^2)

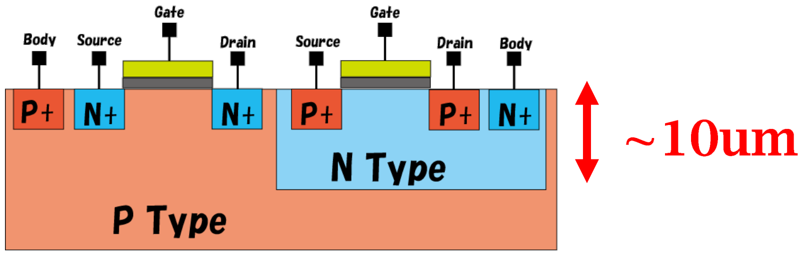


→ Cold amplifier using SOI(Silicon–On–Insulator) technology can achieve these requirements

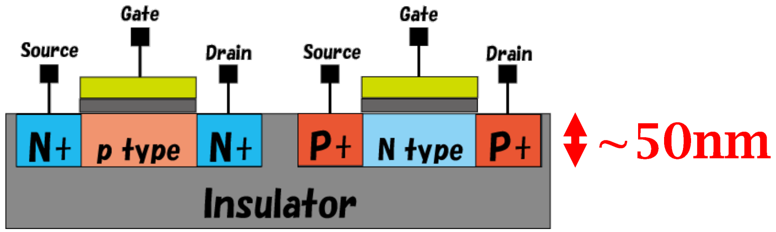
SOI (Silicon-On-Insulator)

- SOI (Silicon-On-Insulator) device was proved to operate at 4K 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)

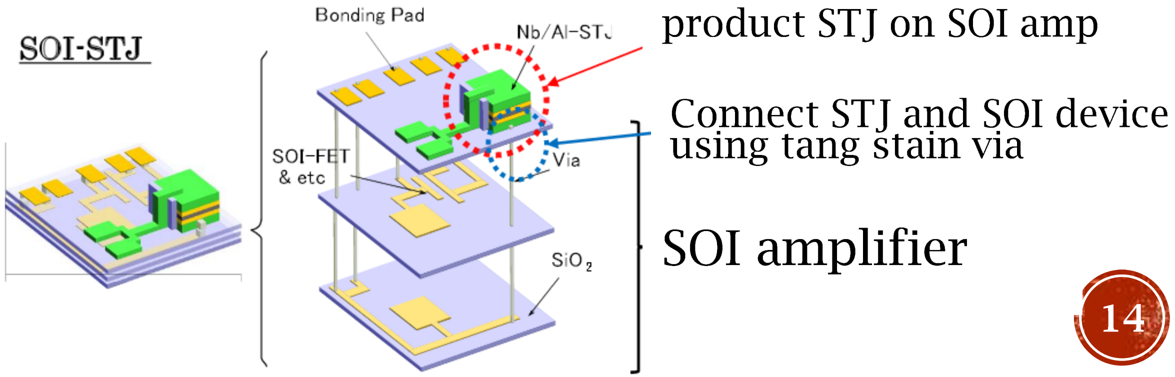
Bulk-CMOS



SOI-CMOS



- We processed Nb/Al-STJ on a SOI amplifier (SOI-STJ)

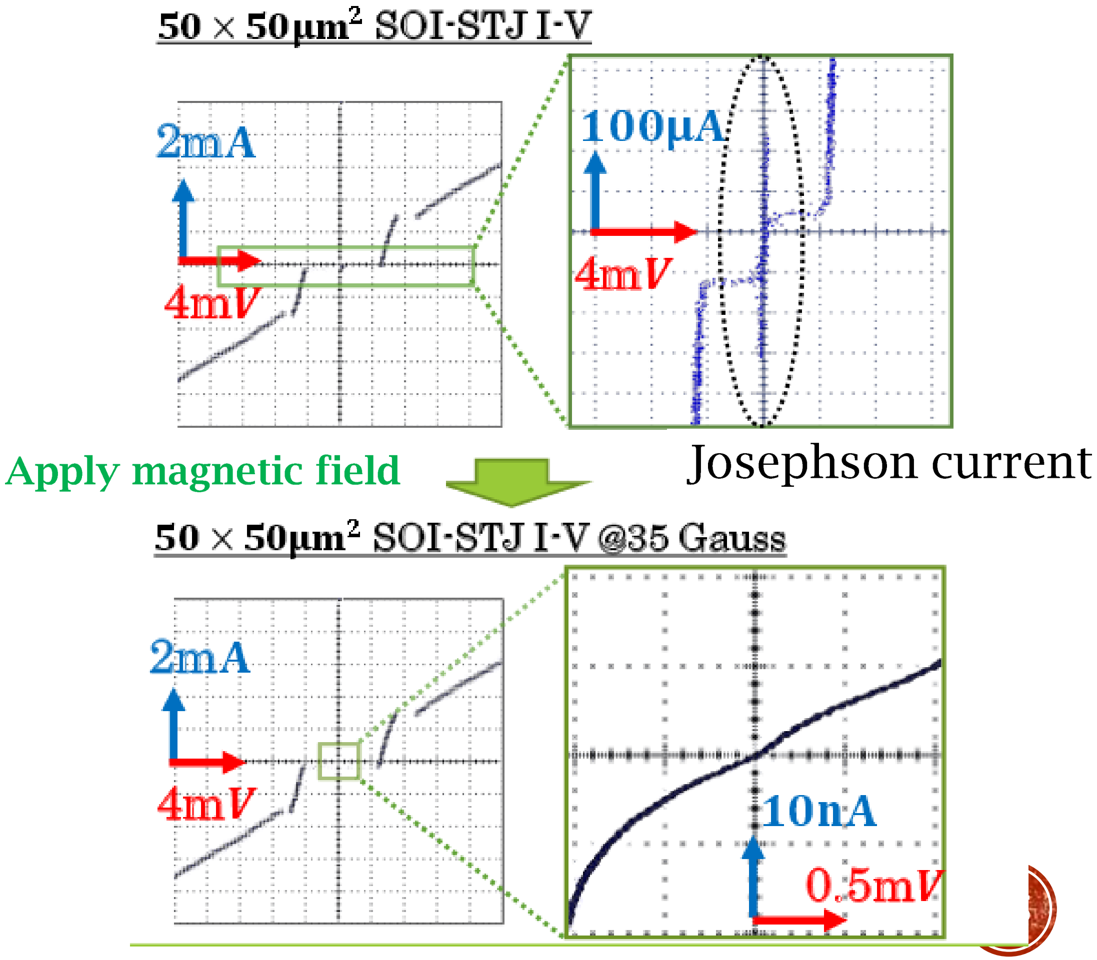


Current status of development of SOI–STJ

- We confirmed performance of Nb/Al–STJ and SOI amplifier in SOI–STJ detector respectively.

- **Nb/Al–STJ**
  We measured the I–V curve of the Nb/Al–STJ(50x50um^2) processed on the SOI wafer at 700mK.
  - Josephson current is observed.
  - Leak current @0.5mV is 6nA
    - It's close to our best record of normal Nb/Al–STJ(100x100um^2) 10nA

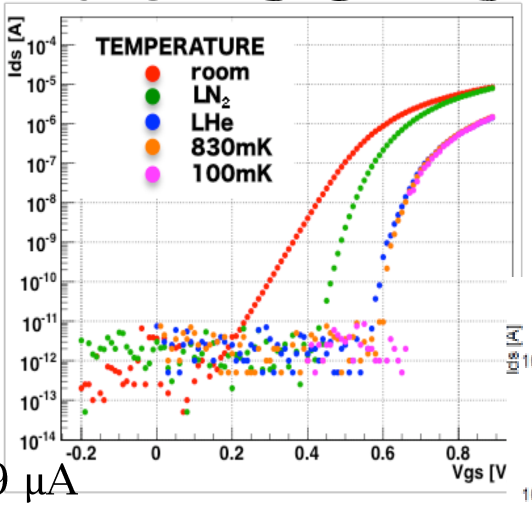
  → Nb/Al–STJ on the SOI amplifier is working well

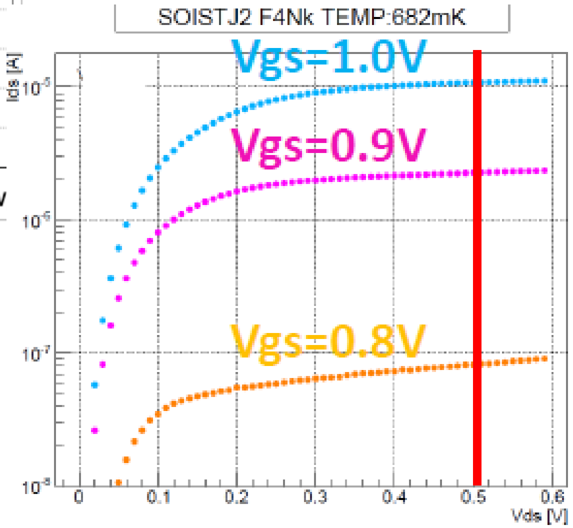


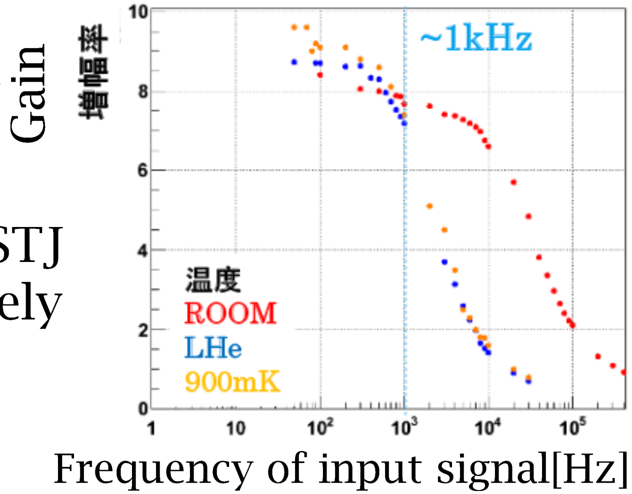
Current status of development of SOI-STJ

- **SOI amplifier**
  - **Temperature dependence**
    - I-V curves at various temperatures
    - SOIFET can be operated at 100mK
  - **Power consumption**
    - Bias voltage of SOIFET in saturation region (red line) : 0.5 V
    - Current (Ids)of FET in saturation region at Vgs = 0.8V : 0.09 μA
    - Power consumption = 0.5 V ×0.09 μA
      = 45 nW/FET for W/L=1.42μm/0.42μm
  - **Frequency response**
    - Approximately 1kHz (requirement: ~MHz)
    - Due to high output impedance, frequency response is not enough.
    - To reduce output impedance, we add buffer circuit in SOI amplifier.

  → Optimization is underway.







We opened up corroboration with AIST
We started using new 3He sorption refrigerator

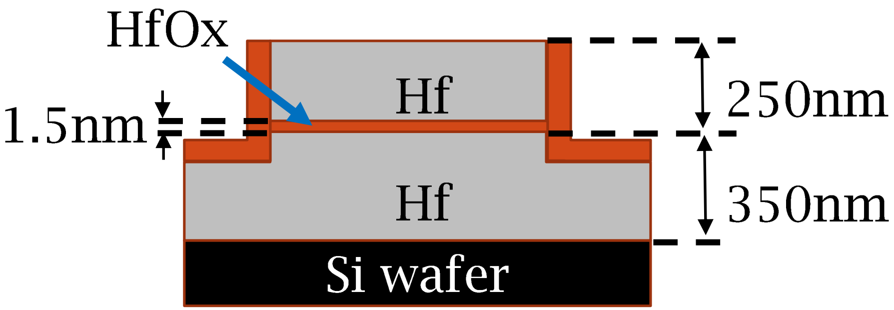
→ Development of SOI-STJ become more effectively

T.Okudaira & R.Senzaki will report more information of development status of cold amplifier tomorrow.

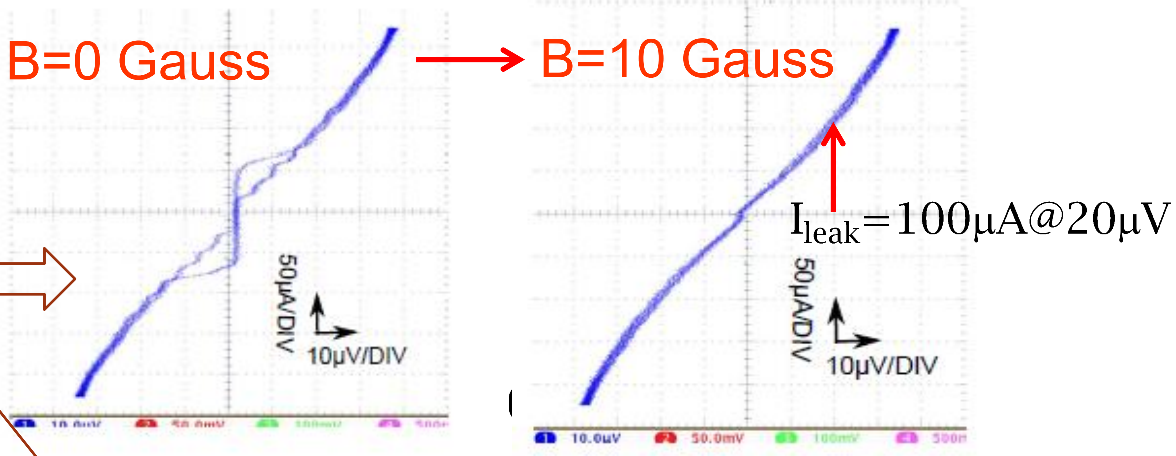
Current status of development of Hf-STJ

- We succeeded in observation of Josephson current by Hf-HfOx-Hf barrier layer.
- However, as our Hf-STJ sample has large leakage current, optimization is underway.

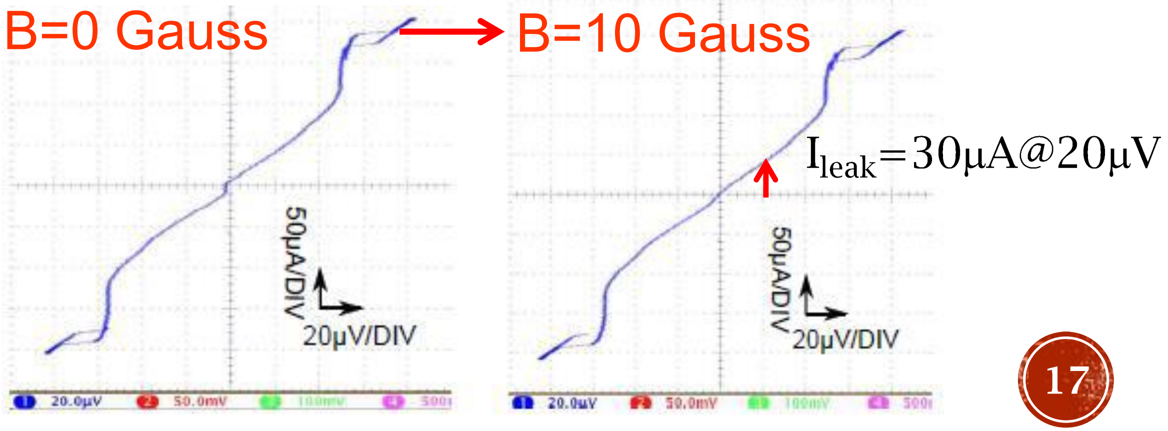
- Downsizing
  - Hf-STJ(100×100μm²) shows smaller leakage current than Hf-STJ(200×200μm²).
- Also we are trying the following
  - Optimize condition for making the insulator.
  - Oxidation on side surface.



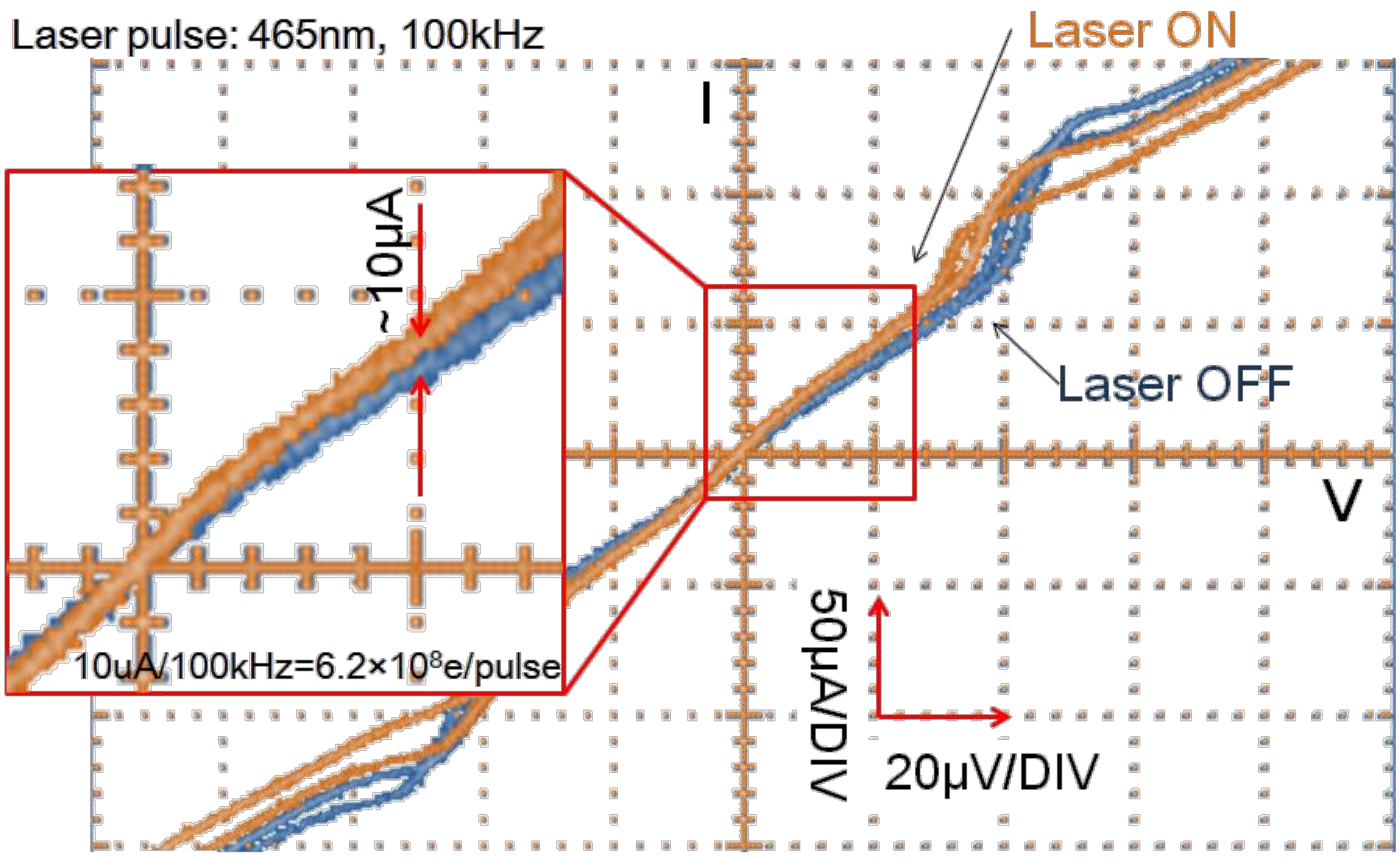
I-V curve of Hf-STJ (**200x200μm²**)
- T~80mK, I_c=60μA, **R_d=0.2Ω**



I-V curve of Hf-STJ (**100x100μm²**)
- T~40mK, I_c=10μA, **R_d=0.6Ω**

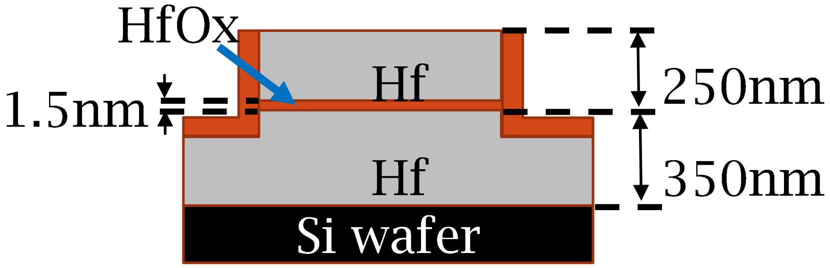


Response to DC light (Hf-STJ)



We observed Hf-STJ response to visible light

- Sample information
  - $100\times100\mu m^2$
  - $R_d = 0.6\Omega$
  - T = 139~153mK



Summary

- We can determine neutrino mass or renew neutrino lifetime lower limit by neutrino decay search experiment.
- We are developing STJ-based detectors to detect a single far-infrared photon in energy range between 15 and 30meV to search for the cosmic background neutrino decay with a rocket or satellite experiment.

- The SOI-STJ detector where Nb/Al-STJ's were processed on a SOIFET board is being developed.

  Both SOIFET and STJ are working well in the SOI-STJ detector below 800mK.

- Hf-STJ response to the visible light was observed.

  Improvement to reduce the leakage current is underway.

BACKUP