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STJ detector developments for the Cosmic Background Neutrino Decay experiment

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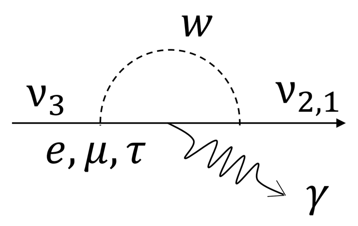
Motivation

COBAND experiment searches for the cosmic background neutrino which is predicted to exist uniformly in the universe.
By the observation of the neutrino oscillation, the neutrino masses were found to be non-zero,
and the mass difference between neutrino generations (m_1, m_2, m_3) has been already established, i.e.



$$|\Delta m_{12}^2| = m_2^2 - m_1^2 \sim 7.37\times10^{-5}\ \text{eV}^2$$
$$|\Delta m_{23}^2| = m_3^2 - m_2^2 \sim 2.46\times10^{-3}\ \text{eV}^2$$

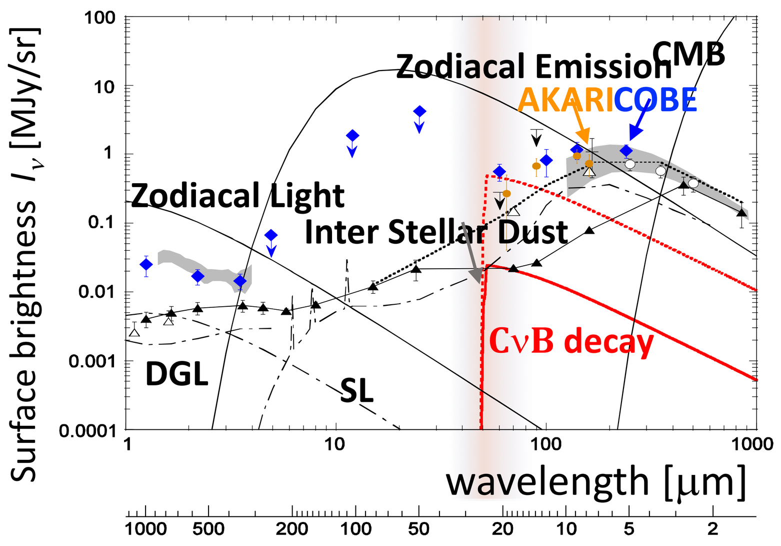
If we assume $m_1^2 \ll m_2^2$, we would obtain

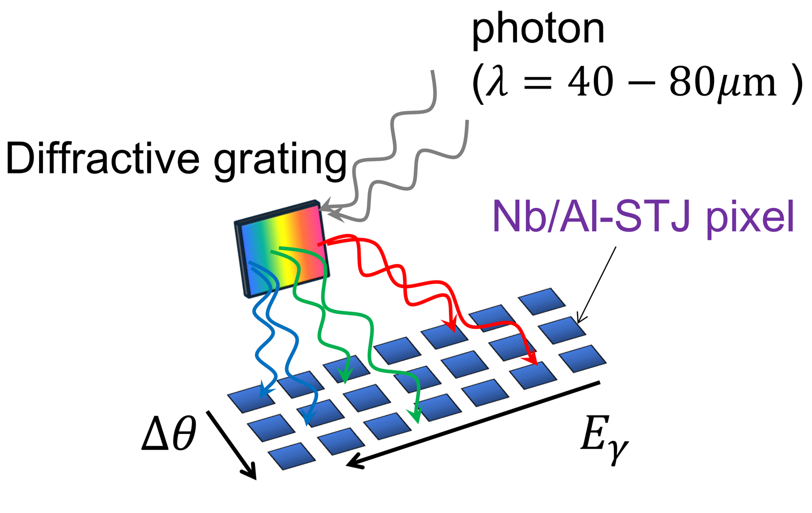
$$m_2 \sim 8.6\ \text{meV, and } m_3 \sim 50.3\ \text{meV}.$$

A heavier neutrino can decay into a lighter neutrino with a photon.

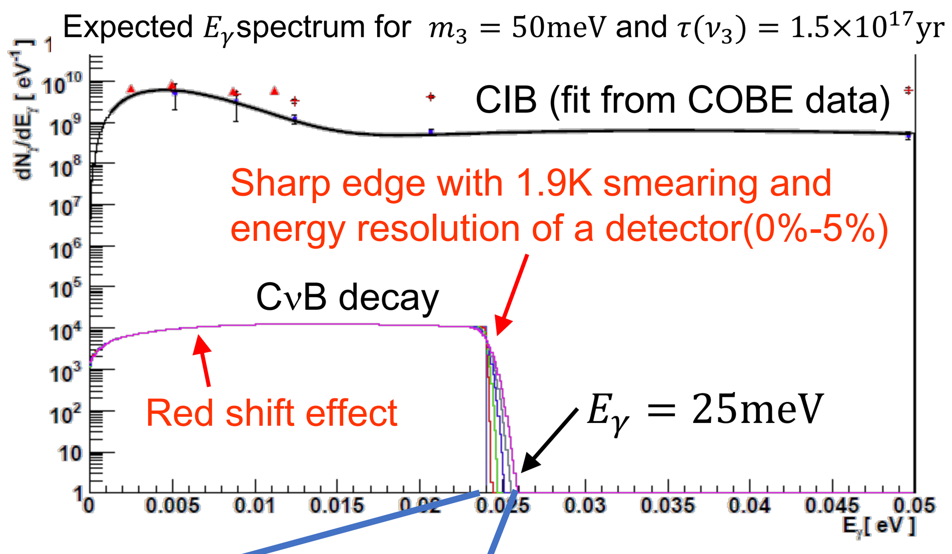
$$\nu_3 \to \nu_2 + \gamma \qquad E_\gamma\ (\text{at } \nu_3 \text{ rest frame}) = \frac{m_3^2 - m_2^2}{2m_3}$$

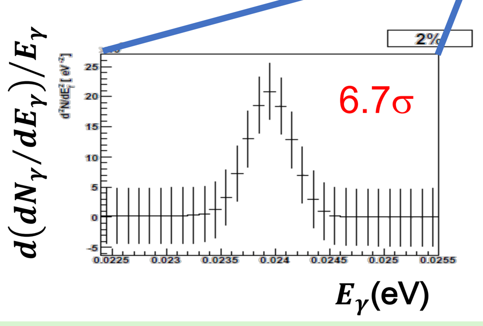
If we assume $m_3 = 50$ meV, E_γ at ν_3 rest frame would be 25 meV, which corresponds to $\lambda_\gamma = 50$ μm. Therefore, by measuring the energy of this photon, we can determine the heavy neutrino mass. The neutrino lifetime is so long, Left-Right symmetric model predict it larger than 10^{17}years, and 10^{12}years or less from COBE and AKARI observation. Thus we search for the photon emission from the decay of the Cosmic Background Neutrino (CνB) in the far infrared region of photon energy spectrum.



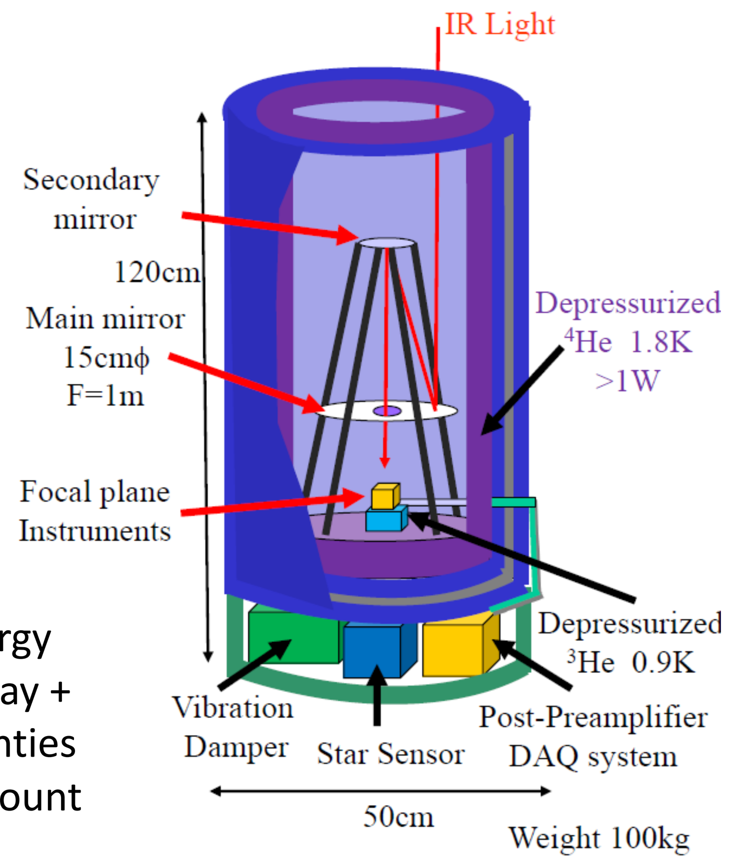


Schematics of telescope





Differential photon energy spectrum from CνB decay + CIB (Statistical uncertainties in N_γ are taken into account in the error bars)

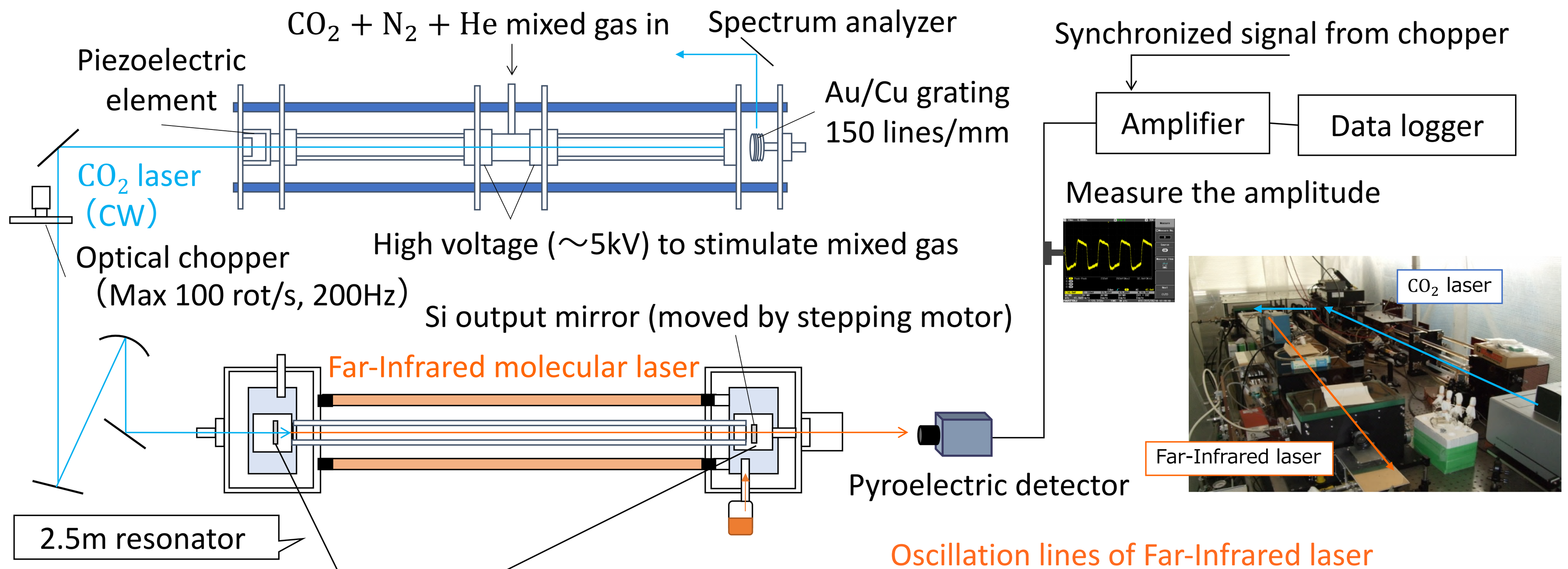


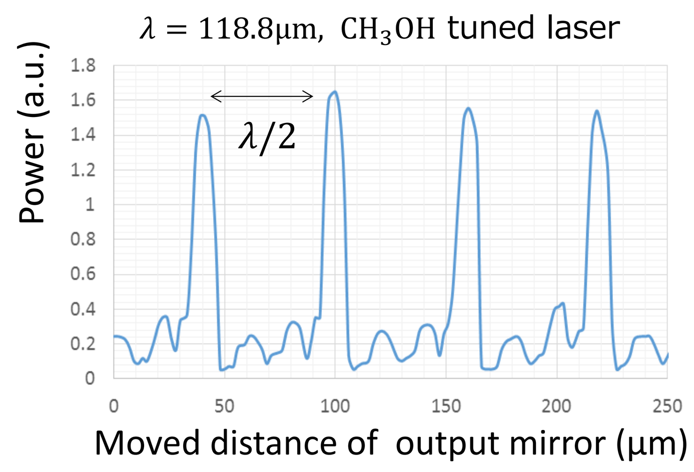
Far-infrared laser for STJ calibration

We're considering to calibrate STJ with Far-infrared molecular laser system (FIR laser) in Fukui university. This system consists from two type of laser- CO_2 laser and FIR molecular laser. First, CO_2 laser excites alcohol gas molecular and next the excited molecules transit to lower energy state, while emitting FIR laser beam. FIR laser…

- oscillates CW(continuous wave) by stimulating alcohol gas by CO_2 laser
- has 70 oscillation lines of wave lengths $\lambda = 40 \sim 700\mu m$ ($E_\gamma = 1.7 \sim 31$meV)

Thus, it fulfill neutrino decay photon energy range ($\lambda = 40 \sim 80\mu m$).

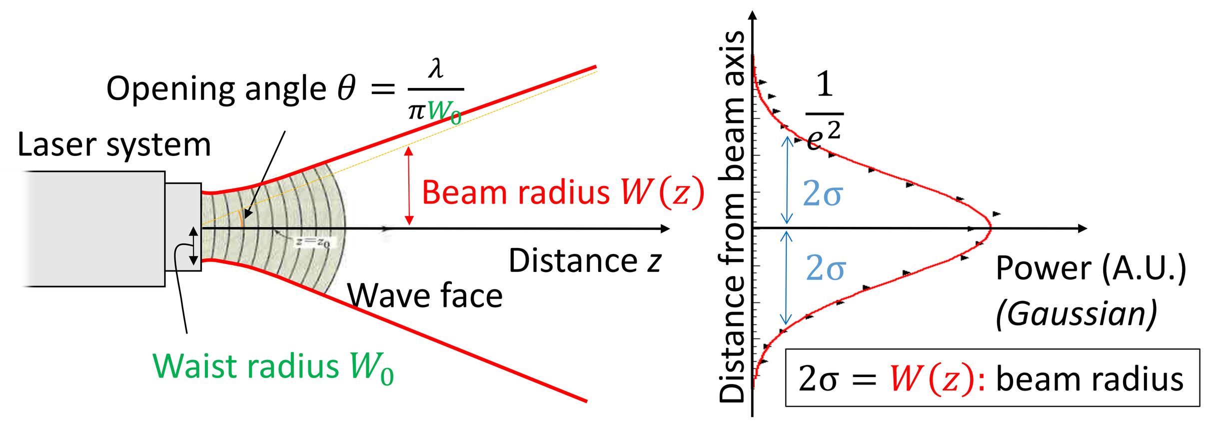


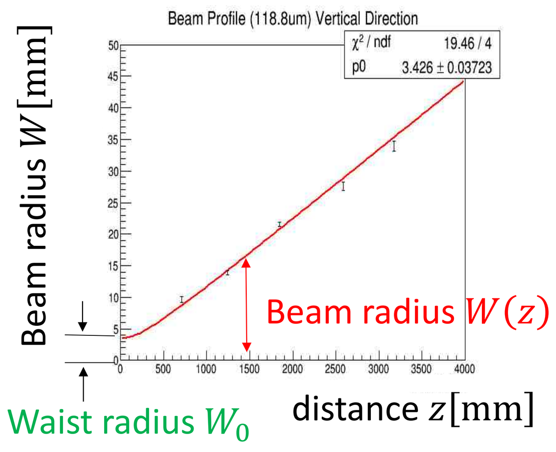


Oscillation lines of Far-Infrared laser

alcohol	λ(μm)	energy(meV)	output(mW)
CD_3OH	43.7	28.4	(6)
CD_3OH	52.9	23.5	4.2
CH_3OD	57.2	21.7	32
CD_3OH	86.4	14.4	(25)
CH_3OH	118.8	10.4	55
CH_3F_2	184.3	6.7	(298)
CH_3Br	245.0	5.1	-
CD_3OH	253.7	4.9	(28)
CH_3Br	264.4	4.7	2
CH_3I	447.2	2.8	13
CH_3CN	453.4	2.7	(0.4)
CH_3Br	545.2	2.3	1
CH_3Br	715.4	1.7	1

The wavelength of FIR laser depends on alcohol molecules, and we measured the wavelength. First out put mirror of FIR laser moves and resonator length changes, while we measure current with pyroelectric detector. In this way we confirmed several oscillation lines like the graph above.



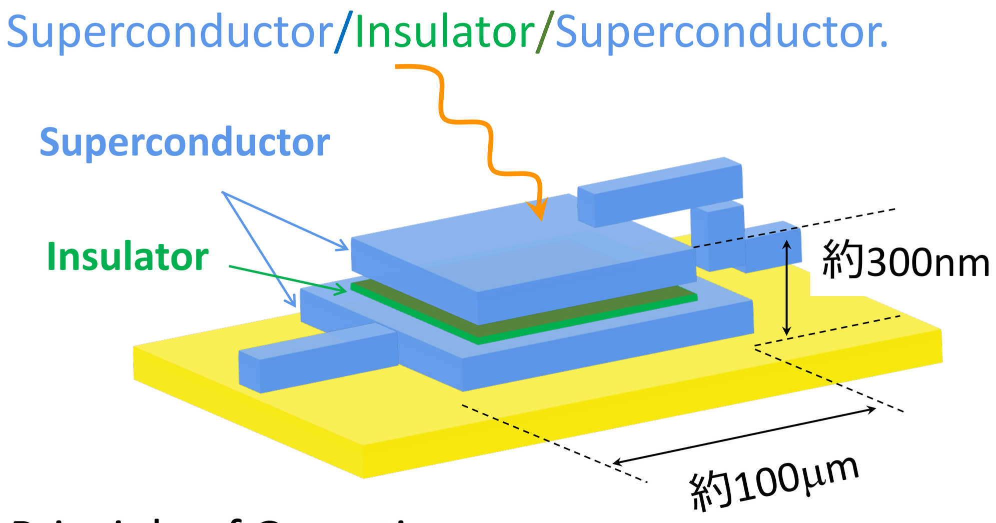


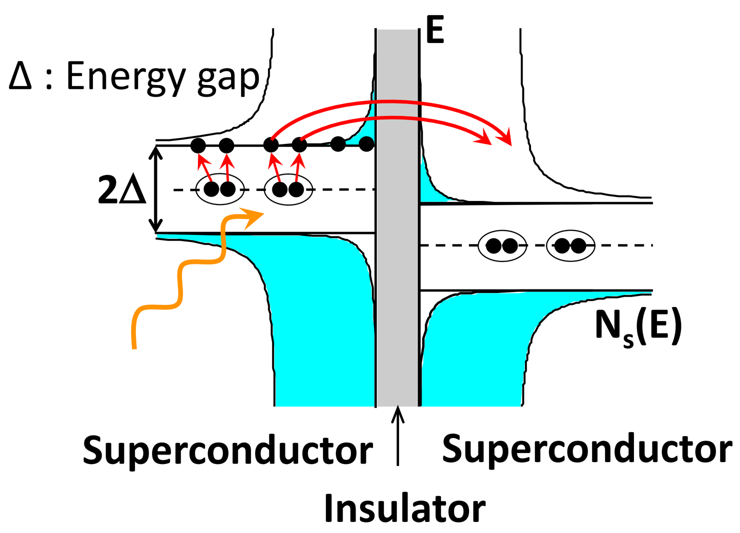
The FIR laser is Gaussian beam, which its intensity follows Gaussian distribution. The laser radius is important parameter to calibrate STJ. We measured intensity distributions with pyro. detector and defined 2σ as beam radius, and fit in Gaussian beam propagation formula:

Beam radius $W(z) = W_0\sqrt{1 + \left(\frac{\lambda z}{\pi W_0{}^2}\right)^2}$. We obtained beam waist radius $W_0 = 3.4$ mm, and opening angle $\theta_0 = 11$ mrad. ($\lambda = 118.8$mm, CO_2 : 9P(36), CH_3OH)

STJ Detector

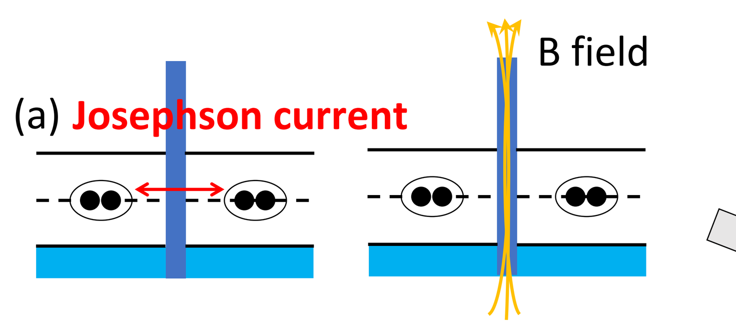
Superconducting Tunnel Junction (STJ) is Josephson device composed of Superconductor/Insulator/Superconductor.



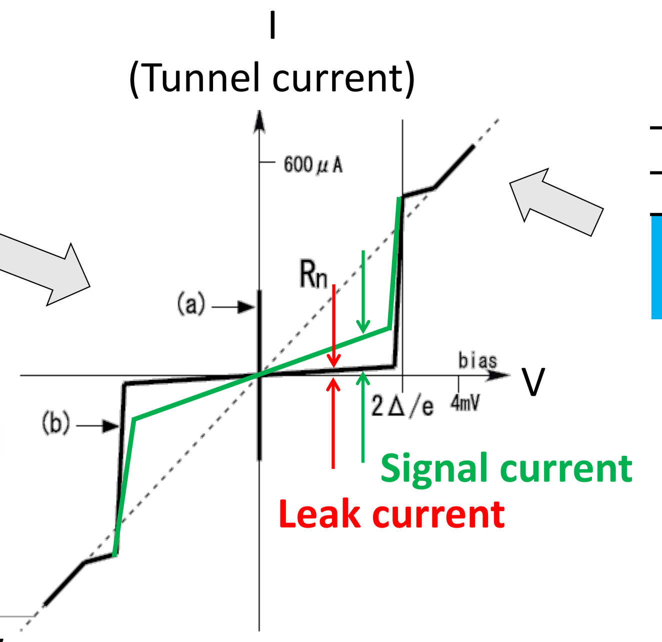


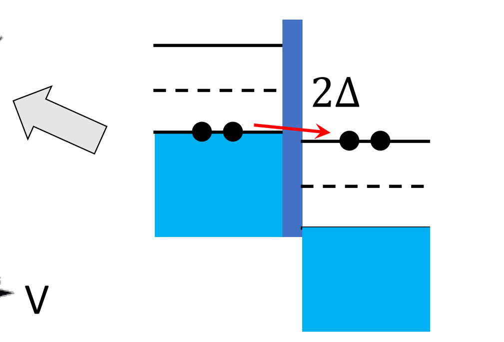
Principle of Operation

1. A constant bias voltage (|V|<2Δ) is applied across the junction.
2. A photon absorbed in the superconductor breaks Cooper pairs and creates tunneling current of quasi-particles proportional to the deposited photon energy.



Tunnel current of Cooper pairs (Josephson current) is suppressed by applying magnetic field.



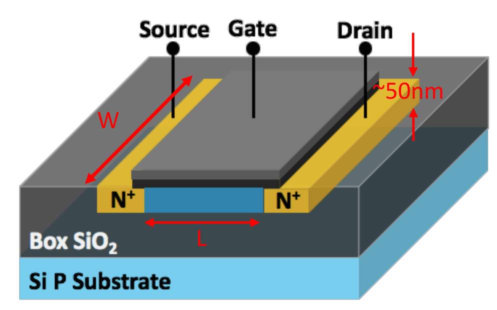


Materials	Energy gap Δ(meV)	transition temp. (K)	Energy resolution (%)
Nb	1.55	9.23	14.8
Al	0.172	1.19	4.9
Hf	0.021	0.165	1.7

Signal : Number of quasi-particles, $N_{q.p.} = G\frac{E_\gamma}{1.7\Delta}$
Resolution: Statistical fluctuation in number of quasi-particles, $\sigma_E/E = \sqrt{(1.7\Delta)F/E}$
→ Smaller superconducting gap energy Δ yields better energy resolution

F: Fano factor (~0.2 for Nb), E: Photon energy, G: Back-tunneling gain

Theoretically Nb/Al-STJ can detect single photon in far-infrared region. However, it has not been achieved due to noise from measurement system. Thus we're considering cryogenic preamplifier placed close to STJ in the refrigerator.

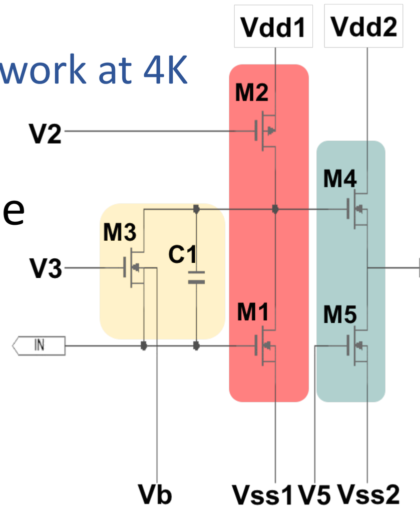


FD-SOI (Fully Depleted-Silicon on Insulator) FET

✓ Very thin channel layer in MOSFET
→ No floating body effect caused by charge accumulation in the body
✓ FD-SOI-MOSFET is reported to work at 4K

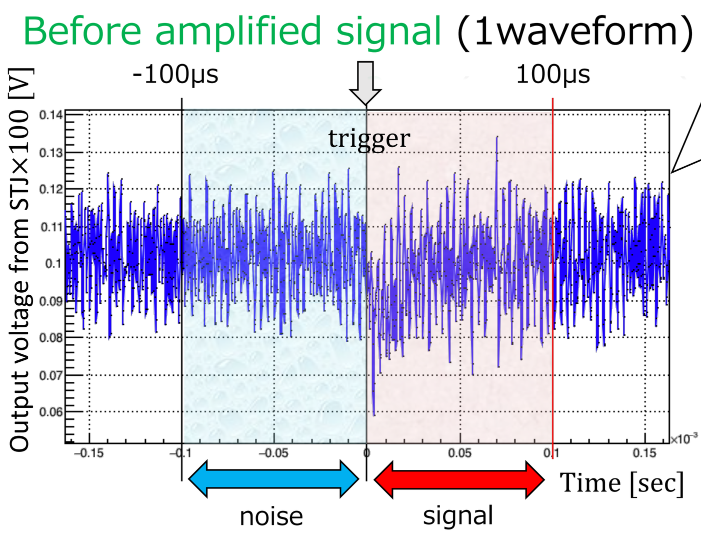
Design of cryogenic preamplifier

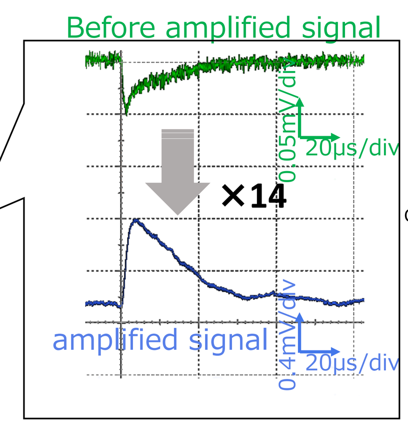
- Common Source Amplifier : MOS-FETs instead of resistance
- Feedback Circuit : Self bias voltage
- Source Follower Circuit : Output impedance is decreased

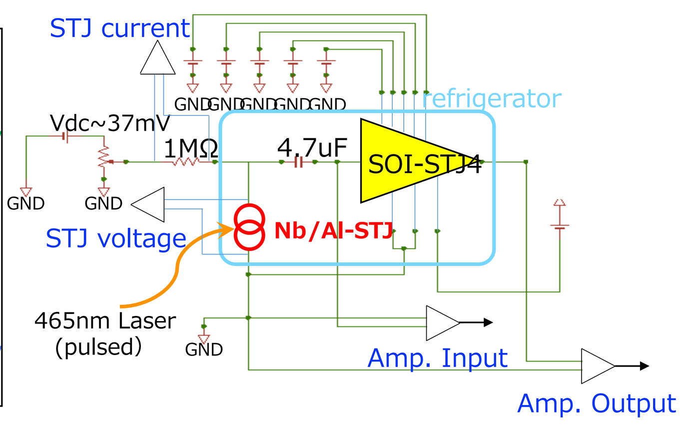


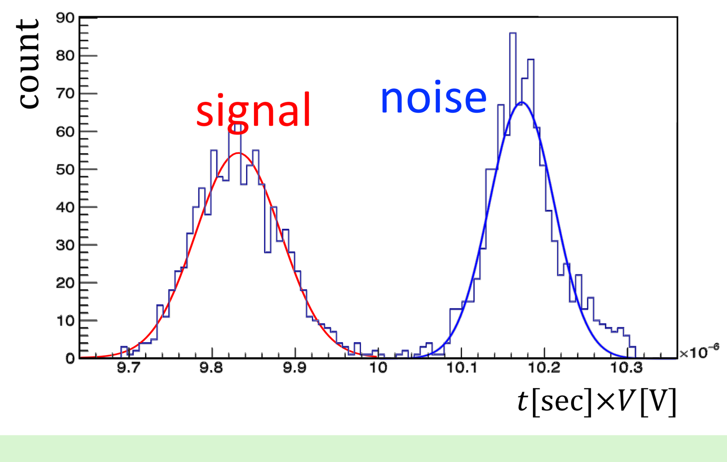
STJ signal amplification with the cryogenic pre-amplifier

I irradiate pulsed laser to STJ and amplify signal from STJ by cryogenic preamplifier.









With signal mean μ_s, noise mean μ_n, noise standard deviation σ_n, S/N is calculated as follows

$$\frac{S}{N} = \frac{\mu_s - \mu_n}{\sigma_n} = \frac{9.832\times10^{-6} - 1.017\times10^{-5}}{3.896\times10^{-8}} \sim 8.68$$

Summary

- We detect amplified STJ signal by cryogenic preamplifier.
- We confirmed the cryogenic preamp. operates at 0.3K.
- We've shown it is possible to evaluate improvement of S/N from before/After amplified signal.