2014/03/19

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Progress Report on "Neutrino Decay Search" project in JFY 2013

1. Motivation of Experiment

The difference between the mass-squares of different-generation neutrinos has been measured by various neutrino oscillation experiments, but the neutrino mass itself has not been measured yet. Detection of neutrino radiative decay enables us to measure a quantity independent of the difference between the mass-squares of different-generation neutrinos. Thus we can determine the neutrino mass itself from these two independent measurements, the neutrino oscillation and the neutrino radiative decay. The heaviest neutrino ν_3 decays into a lighter neutrino ν_2 and a photon via a Feynman diagram as shown in Fig. 1.As the neutrino lifetime is so long as to be much larger than the age of the universe, the most promising method is to observe the decay of the cosmic background neutrino. The cosmic background neutrino has a temperature of 1.9K and a particle density of 110 cm^{-3} per generation. If a neutrino decays at rest, the decay photon energy E_γ is given by $E_\gamma=\Delta m^2_{32}/2m_3$ where Δm^2_{32} is the mass-square difference between ν_3 mass m_3 and ν_2 mass m_2. By measuring E_γ in neutrino decay, we can determine the neutrino mass itself. We search for the neutrino radiative decay under these constraints on the mass-square differences and the mixing angles between the neutrino generations. Assuming the m_3 is between 50meV and 150meV, the decay photon energy at ν_3 rest frame (E_γ) is between 10meV and 25meV which is far-infrared region. The photon energy spectrum from neutrino decay has a shape as shown in Fig.2 which has a sharp cutoff at the high energy end $E_\gamma=\Delta m^2_{32}/2m_3$ and a tail in the low energy side due to a red shift effect. For this search, we make a fit of the photon energy spectrum of Cosmic Infrared Background (CIB) to a sum of a neutrino decay photon energy spectrum and a continuum spectrum. The continuum of the CIB is the background against the neutrino decay signal. In the above far-infrared region between 10meV and

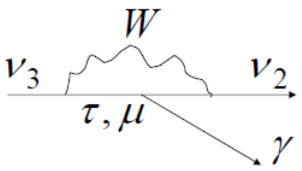

Fig1. $\nu_3 \rightarrow \nu_2 + \gamma$ Feynman Diagram

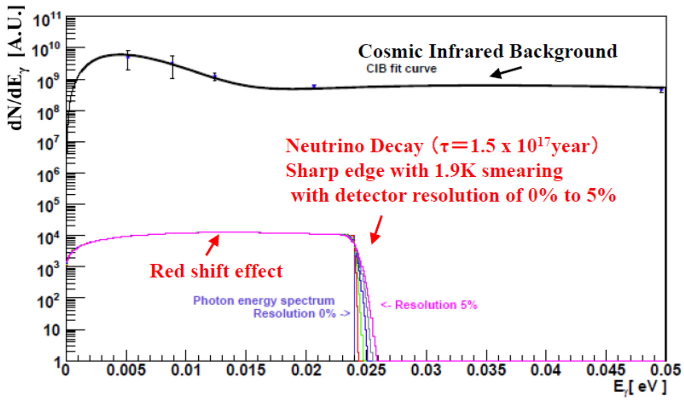

Fig.2. Energy spectrum of photons from neutrino decay with various energy resolutions from 0% to 5% (lower curves) and foreground from Cosmic Infrared Background (CIB) radiation (upper curve)

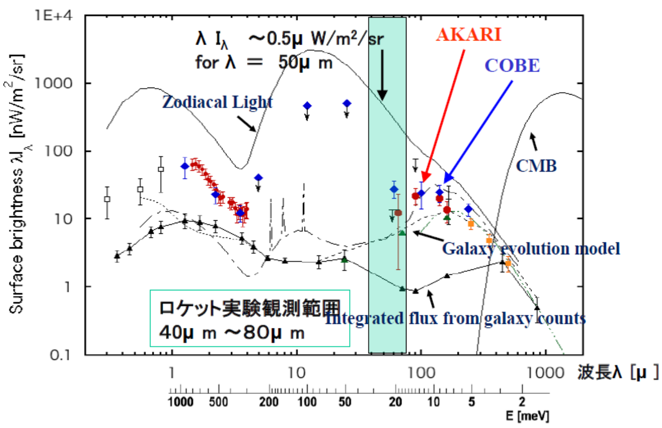

Fig.3. Cosmic Infrared Background measurement results by COBE (blue diamonds) and AKARI (red circles).

25meV, only two satellite observatories of COBE and AKARI have measured this CIB in 1998 and 2011, respectively, as shown in Fig. 3. Using AKARI CIB results, we determined the lower limit of neutrino lifetime to be (3.1～3.8) x 10^{12} years at 95% C.L. for m_3 between 50meV and 150meV [1].

In the left-right symmetric model, the neutrino lifetime is predicted to be 1.5 x 10^{17} years at minimum. We made a feasibility study of the neutrino decay search in the CIB energy spectrum measurement. Neutrino decay signal rate is expected to be 50 sec^{-1} with a telescope of 20 cm diameter and a viewing angle of 0.1 degrees for neutrino lifetime of 1.5 x 10^{17} years. The CIB values measured by COBE and AKARI give a signal-to-noise ratio of 2 x 10^{-5}, when the energy resolution of the detector is better than 2%. We can expect to observe the neutrino decay signal with 5σ significance by 6-hours measurement with this telescope. We published these results in JPSJ on January 2012 with a title of "Search for Radiative Decays of Cosmic Background Neutrino using Cosmic Infrared Background Energy Spectrum" [1].

2. Superconducting Tunnel Junction (STJ) Detector and Experimental Apparatus

We have worked on the experimental design and the research and development of the detector for the neutrino decay search experiment. In this experiment, 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. A heavier neutrino decays into a lighter neutrino with an infrared photon. To detect this signal, we need measure the energy spectrum of the cosmic infrared photon background with energy resolution better than 2%. We adopted a Superconducting Tunnel Junction (STJ) detector as such a detector.

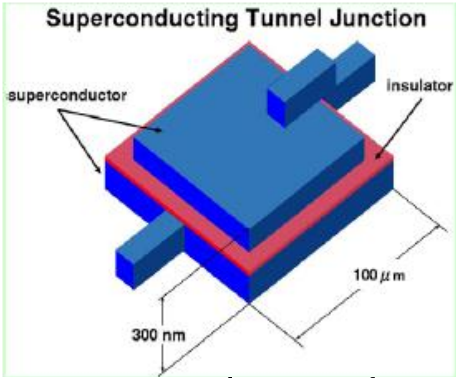

Fig.4. structure of Superconducting Tunnel Junction detector.

The STJ has a sandwich structure of superconductor and insulator as shown in Fig.4. By measuring the tunnel current of electrons (quasi-particles) excited by an incident particle, we can measure the energy of the incident particle. The number of excited quasi-particles is inversely proportional to the energy gap Δ of the superconductor. The energy gap Δ of superconductors are shown in Table 1. As the energy gaps of the superconductors are much smaller than those of semiconductors, the detection of far-infrared photon with STJ has much better efficiency than the present far-infrared detector.

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

Table 1. Critical temperature Tc and energy gap Δ of superconductor .

We have worked on the research and development of STJ photon detector to detect the far-infrared photon since 2006. We have studied the characteristics of Nb/Al-STJ detector as shown in Fig.5 and Hf-STJ detector.

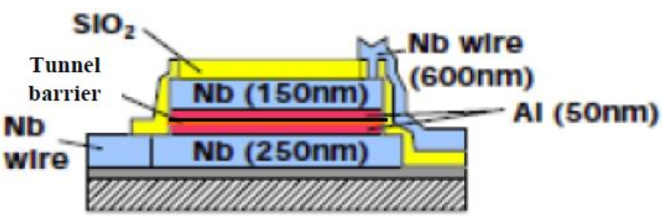

Fig.5. structure of Nb/Al-STJ detector.

Hf-STJ has better energy resolution than Nb/Al-STJ because it has 10 times more excited quasi-particles, but need much lower temperature to operate as a STJ than Nb/Al-STJ. We are developing both Nb/Al-STJ and Hf-STJ. We succeeded in measuring X-ray photon energy and detecting visible photons with our Nb/Al-STJ photon detector. We also succeeded in producing Hf-STJ photon detectors which work as STJ for the first time in the world. We reported these results

titled with “Development of Superconducting Tunnel Junction Photon Detector using Hafnium” in the international conference on Technology and Instrumentation in Particle Physics 2011 (TIPP 2011), Chicago, in June 2011[2].

Our purpose is to measure CIB energy spectrum with a telescope of 20 cm diameter and a viewing angle of 0.1 degree installed on a satellite with more than 6-hour running time to observe the decay of cosmic background neutrino with lifetime of 1.5 x 10^{17} years at 5 σ significance. For this purpose, we plan to do a preparatory rocket experiment in 2017. In this rocket experiment, we will use a multi-pixel Nb/Al-STJ detector with a grating and three mirrors installed in a 0.9K cryostat as shown in Fig.6. We will take data for 5 minutes at 200km height in this experiment and can improve the neutrino lifetime limit by one order. To do this rocket experiment in 2017, we have to complete the R&D of the Nb/Al-STJ photon detector, the readout electronics, the optical elements and the cryostat, and start production of whole detector in 2015. We are collaborating with a JAXA cosmic infrared background team headed by Dr. Shuji Matsuura and will propose this rocket experiment to JAXA as soon as completing the detector R&D.

Then in the next stage we will install this detector in a satellite, and perform a satellite experiment for the cosmic background neutrino decay search around 2020. As a detector installed in the satellite, we have two designs: the base design is Nb/Al-STJ with a grating and the alternative is a Hf-STJ micro-calorimeter.

The collaboration members of this project are from University of Tsukuba, Okayama University, RIKEN, University of Fukui, Kinki University, JAXA/ISAS, KEK, SNU and Fermilab. The research and development of the following subjects are being and will be done by this collaboration: Nb/Al-STJ, far-Infrared light source, 0.9K cryostat installed in a rocket, optical system such as a grating, Hf-STJ, and electronics such as preamplifiers working at very low temperature around 0.9K

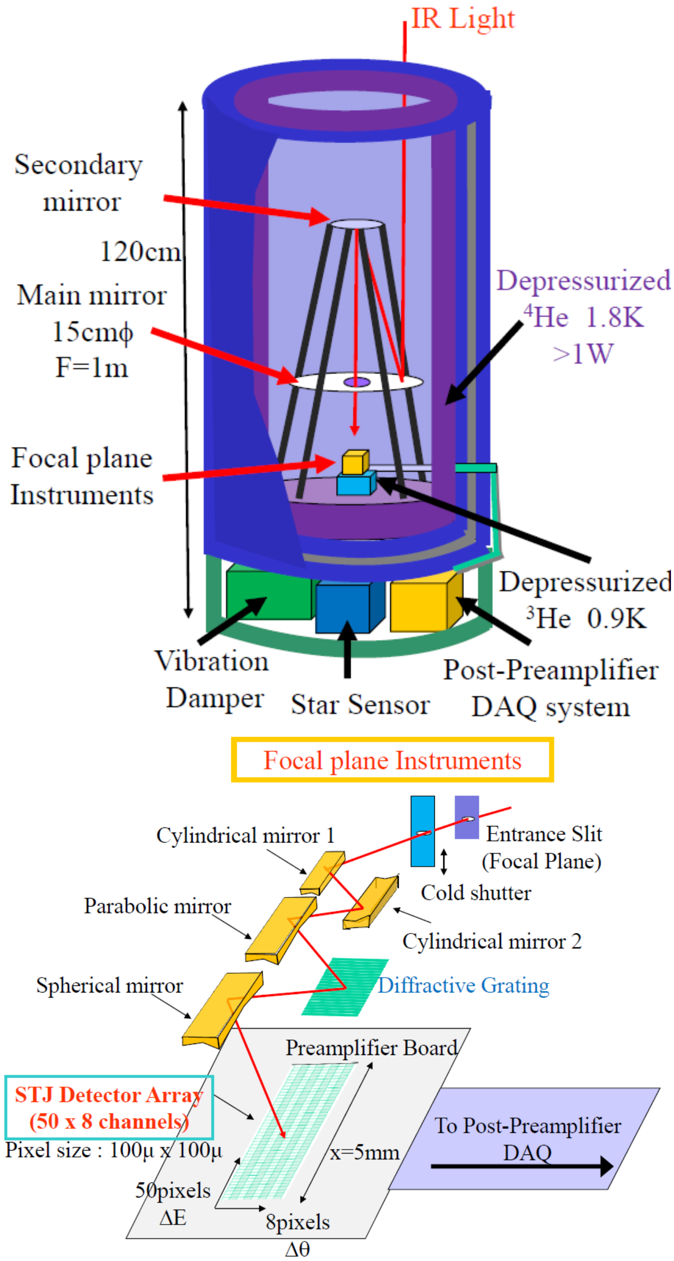

Fig.6. Apparatus of the rocket experiment for neutrino decay search

3. Progress in JFY2013

In JFY2013, we have worked on the development of Superconducting Tunnel Junction (STJ) detector for the neutrino decay search experiment and obtained the following results [3-8]:

About Hf-STJ detector, we observed the response of a Hf-STJ detector with a size of 100μm x100μm to DC-like laser light at wavelength of 465nm and a frequency of 100kHz at temperature

around 50mK by using $^3He/^4He$ dilution refrigerator as shown in Fig. 7. The signal current was measured to be 10μA at 20μV. The work to decrease the leakage current by decreasing the Hf-STJ size is underway.

We observed that the leakage current of Nb/Al-STJ (junction size of $100x100\mu m^2$) decreased rapidly as the temperature decreased. The leakage current measured at V = 0.5mV changed from 20μA to 10nA as the temperature decreased from 1.8 K to 0.9 K as shown in Fig.8a. We measured the I-V curve of small size Nb/Al-STJ (junction size of $4\mu m^2$) at 1.8K to see the leakage current dependence on junction size. The leakage current at 0.5mV was 10nA as shown in Fig. 8b, which was smaller than the STJ with junction size of $100x100\mu m^2$ by a factor of 1/2000 while the junction area was smaller by a factor of 1/2500. The leakage

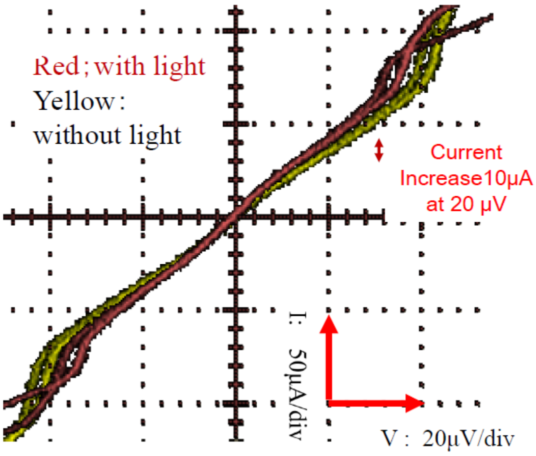

Fig.7. I-V curve of Hf-STJ with and without 100kHz laser light (465nm) at T ～ 50mK.

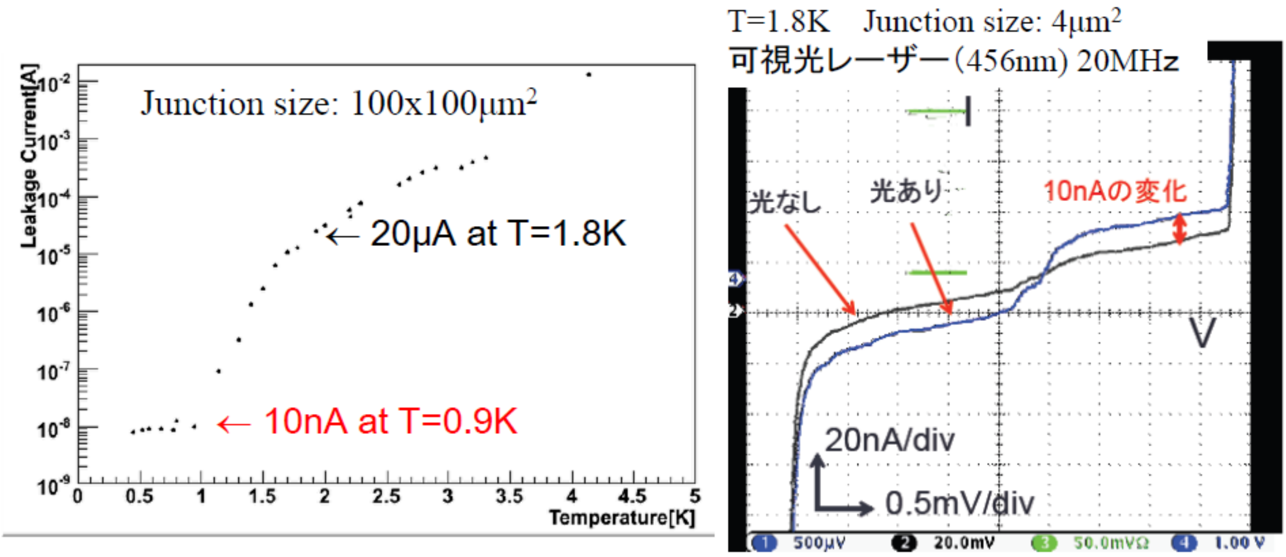

Fig.8.(a) Leakage current of Nb/Al-STJ as a function of temperature and (b) I-V curve of another small-size Nb/Al-STJ(4 μm^2) with and without DC-like laser light at T = 1.8K

current was found to be proportional to the junction size approximately. We observed the STJ response to DC-like laser light with wavelength of 465nm and frequency of 20MHz in the I-V curve as shown in Fig.8b.

The response of Nb/Al-STJ (junction size of $100x100\mu m^2$) to infrared laser pulse light of wavelength 1.31 μ is shown in Fig.9. The Nb/Al-STJ was operated at T = 1.8 K with a depressurized He refrigerator. When we injected infrared laser light in 10 pulses during 200 ns, we observed the Nb/Al-STJ signal has a time spread of 1μs as expected and estimated that the number of photon detected is 93±11 from the spread of the signal charge distribution and the noise magnitude in RMS corresponds to (19±2) photons. Next we observed the response of small-size Nb/Al-STJ

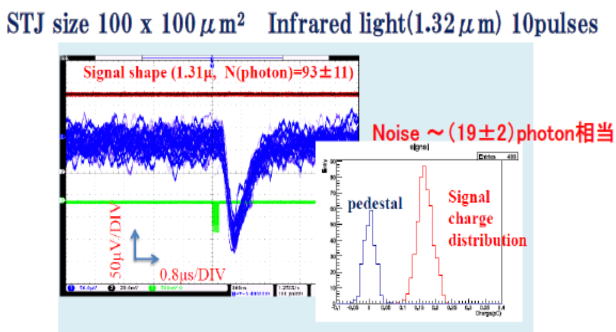

Fig.9. Response of Nb/Al-STJ with a junction size of 100x100 μm^2 to infrared laser pulse light of wavelength 1.31μ, and the signal charge distribution.

(junction size of 4μm[2]) to visible laser pulse light of wavelength 456nm. We estimated the number of photon detected to be 0.93±0.19 by fitting the signal charge distribution to a Poisson distribution smeared by Gaussian with the same sigma as pedestal sigma. The noise magnitude corresponds to (2.5±0.4) photons as shown in Fig.10. The signal-to-noise ratio was improved by a factor of 30 compared with the measurement in JFY2012 by improving the measurement setup and STJ operation parameter, and decreasing the STJ junction size.

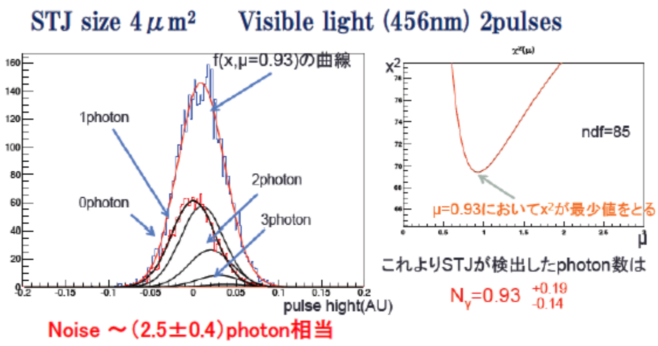

Fig.10. Signal charge distribution of Nb/Al-STJ with a junction size of 4μ m^2 by visible laser pulse light of wavelength 465nm.

As we aim at 5σ separation of one far-infrared photon signal from pedestal, we need further improvement by developing a low-noise preamplifier working at very low temperature around 0.9K such as a Silicon-On-Insulator (SOI) preamplifier or a High-Electron-Mobility-Transistor (HEMT) preamplifier. We have developed a SOI-STJ combined detector and a HEMT preamplifier. We made a SOI-STJ combined test sample where we processed Nb/Al-STJ on a 2.9mm x 2.9mm SOI transistor board as shown in Fig.11. PMOSFET's and NMOSFET's were made on this SOI board. We measured I-V curves of Nb/Al-STJ and SOI MOSFET and confirmed that both Nb/Al-STJ detector and SOI MOSFET worked normally at 750mK as shown in Fig.12.

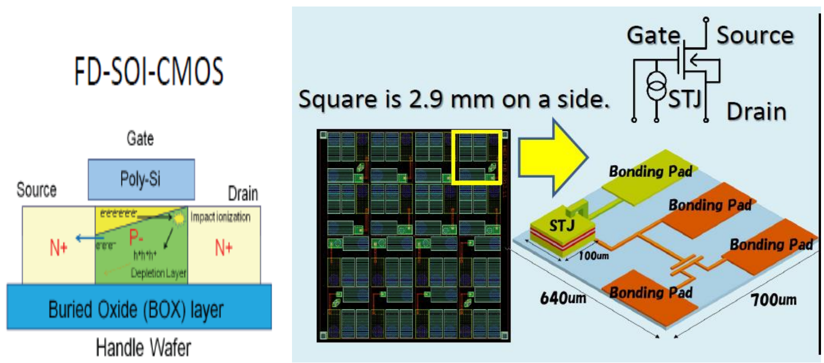

Fig. 11. (Left) SOI transistor structure and (Right) SOI-STJ detector where Nb/Al-STJ's were processed on a SOI transistor board.

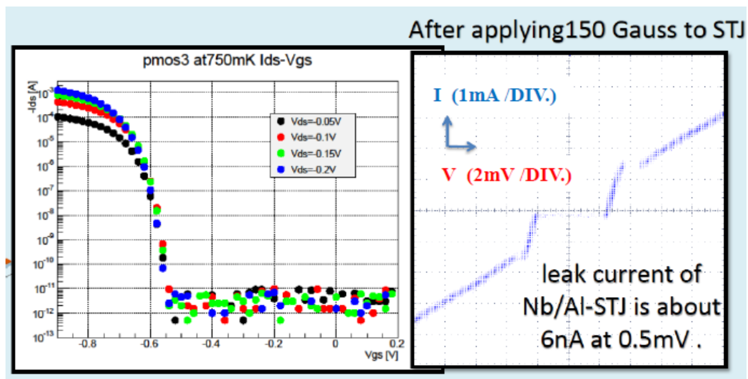

Fig.12. (Left) I-V curve of SOI PMOSFET and (Right) I-V curve of STJ after applying magnetic field of 150G..

Then we made the second version of SOI-STJ (SOI-STJ-v2) prototype to see the STJ response amplified with the SOI transistor. The SOI-STJ-v2 circuit design and the simulation results are shown in Fig.13. In this circuit design, we put a capacitance between STJ and SOI FET gate in order to apply a DC voltage on the SOI FET gate independently of the STJ operation voltage. The simulation

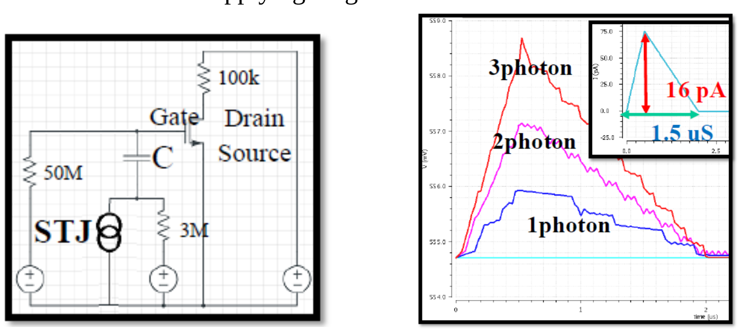

Fig.13. (left) SOI-STJ-v2 circuit design and (Right) the simulation output of SOI-STJ-v2.

results predict that STJ signal for a single photon with wavelength of 50μm gives an SOI drain voltage change of 1mV as shown in Fig.13, which is enough large to be detected. We measured the amplification gain of the SOIFET using a sine wave input and found it to be 27 as expected in the design. The study of the SOI-STJ-v2 response to photons is underway.

Fig.14. (Left) ADR setup at Fermilab MilliKelvin Facility and (Right top) Four Japanese graduate students and staffs and Fermilab collaborators are working on the test of Nb/Al-STJ and low temperature preamplifier (Right bottom) at Fermilab.

We also developed HEMT preamplifiers designed by Fermilab group which work at low temperature around 2K. We started making a test setup of HEMT preamplifier with Nb/Al-STJ at Fermilab. In JFY2013, we have tested Nb/Al-STJ and low-temperature preamplifier at Fermilab during three weeks in August, three weeks in September and three weeks in February thru March 2014. Japan-US collaboration team worked on the setup construction as shown in Fig.14. We measured the I-V curve of Nb/Al-STJ and preamplifier at 1.5K at Fermilab VTS (Vertical Test Stand) setup in summer 2013. We observed the response of Nb/Al-STJ to visible laser pulse light at 0.9K using ADR (Adiabatic Demagnetization Refrigerator) setup at Fermilab MilliKelvin Facility in winter 2014. We could confirm that both the STJ and the HEMT preamplifier work at very low temperature. We plan to perform a combined test of the Nb/Al-STJ and the low-temperature HEMT preamplifier in August 2014.

Far-infrared light source with wavelengths of 44, 53, 86, 119 and 454μ and a pulse width of 10μs was successfully made using a CO_2 laser and gasses such as CH_3OH and CD_3OH at University of Fukui. As a next target, 1μs width beam is being developed.

Equipment for data transfer from a rocket to the ground is under investigation. Data transfer rate is required to be larger than 3.1 Mbps from the data size and rate. The present candidate of the equipment has a data transfer rate of 10 Mbps.

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