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Development FD-SOI MOSFET amplifiers for integrated read-out circuit of superconducting-tunnel-junction single-photon-detectors

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We proposed a new high resolution single photon infrared spectrometer for search for radiative decay of cosmic neutrino background(CνB). The superconducting-tunnel-junctions(STJs) are used as a single photon counting device. Each STJ consists of Nb/Al/Al_xO_y/Al/Nb layers and their thicknesses are optimized for the operation temperature at 370 mK cooled by a ^{3}He sorption refrigerator. Our STJs achieved the leak current 250 pA and the measured data implies that a smaller area STJ fulfills our requirement. FD-SOI MOSFETs are employed to amplify the STJ signal current in order to increase signal-to-noise ratio(S/N). FD-SOI MOSFETs can be operated at cryogenic temperature of 370 mK, which reduces the noise of the signal amplification system. FD-SOI MOSFET characteristics are measured at cryogenic temperature. The Id-Vgs curve shows a sharper turn on with a higher threshold voltage and the Id-Vds curve shows a non linear shape in linear region at cryogenic temperature. Taking into account these effects, FD-SOI MOSFETs are available for read-out circuit of STJ detectors. The bias voltage for STJ detectors are 0.4 mV and it must be well stabilized to deliver high performance. We proposed an FD-SOI MOSFET based charge integrated amplifier design as a read-out circuit of STJ detectors. The requirements for an operational amplifier used in the amplifier is estimated using SPICE simulation. The op-amp required to have a fast response(GBW$\geq$100 MHz) and it must have low power dissipation as compared to the cooling power of refrigerator.

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1 Introduction

S.Kim. et al. proposed an experiment which is to search for cosmic neutrino background decay [1]. The final goal of this experiment is to measure the mass of neutrino. Various neutrino oscillation experiments measured the neutrino mass squared differences and measured neutrino mass squared difference between m_2 and m_3 is measured to be an equation 1 [2].

$$\Delta m_{32}^2 = m_3^2 - m_2^2 = (2.44 \pm 0.06) \times 10^{-3}\ \mathrm{eV}^2 \tag{1}$$

These results indicate that the neutrinos have non zero mass and heavier neutrino(ν_3) can decay into lighter neutrino(ν_2) with photon. The energy of photon from neutrino radiative decay is written as equation 2.

$$E_\gamma = \frac{m_3^2 - m_2^2}{2m_3} \tag{2}$$

Once the energy of this photon is measured, the mass of neutrino(m_3) is easily calculated since numerator is already measured as equation 1. It seems difficult to measure the energy of photon taking in to account extreamly long lifetime of neutrino. Figure 1 left shows a Feynman diagram of $\nu_3 \rightarrow \nu_2$ neutrino radiative decay

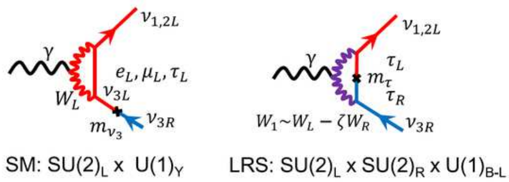

Figure 1: $\nu_3 \rightarrow \nu_2 + \gamma$ Feynman Diagram in SM(left) and in LRSM(right).

in the Standard Model. Assuming $m_3 = 50$ meV/c^2, the lifetime of ν_3 is predicted to be in the order of 10^{43} years with this process. Although, in the Left Right Symmetric model(LRSM), figure 1 right process also contributes to the neutrino radiative decay. This additional process drastically enhances the decay rate and it is predicted to be the order of 10^{17} years with the values from recent experimental limits [1]. The cosmic neutrino background(CνB) which fills the universe with a particle density ρ of 110 cm^{-3} per generation is an ideal neutrino source, since it provides uniform temperature(1.9 K) enormous number of neutrinos. The spectrum of CνB decay is well known. The energy of the photons from the CνB decay were monochromatic photons when they were emitted and the red shift produces a tail on a long wavelength side. Main background is zodiacal emission(ZE) which is produced by thermal emission from space dust in the solar system. The magnitude of zodiacal emission is $\mathcal{O}(10^2)$

larger than the CνB decay spectrum. The CνB decay is measureable thanks to the well known spectrum. Actually, S.Kim. et al. measured the lifetime of neutrinos with this method and set the current experimental limit on the lifetime. It is in the order of 10^{12} years [3]. We plan a rocket experiment for improving this limit to 10^{14} years as a next step. We proposed a new high-resolution infrared spectrometer for this experiment. Our detector system consists of three components similar to the general spectrometer. Incident infrared photons(40 um - 80 um) are spacially distributed depending on their energy by the diffractive grating. Superconducting tunnel junctions(STJs) are employed to detect the diffracted photons, since it can detect the single infrared photons. Single photon counting method suppress the dark noise contamination on signal to less than or comparable to ZE on sensitivity degradation. The fully-depleted silicon-on-insulator(FD-SOI) MOSFET based cold amplifiers are used to amplify the signal current from the STJs. Following sections describe the status of STJ and cold amplifier development.

2 Superconducting Tunnel Junction

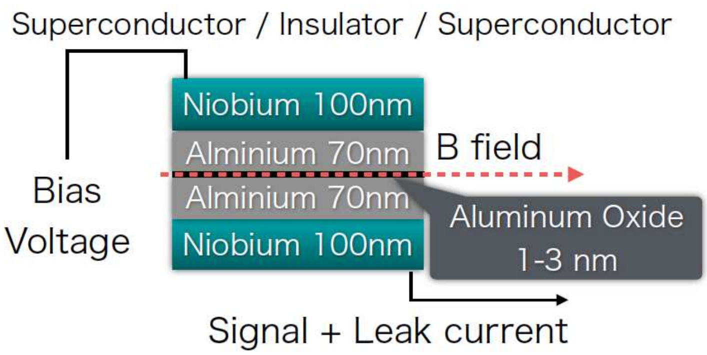

Figure 2: Cross-section of our STJ.

Figure 2 is a cross-section of our STJ. The STJs were fabricated in the clean room for analog-digital superconductivity (CRAVITY) in AIST. Each of our STJ consists of Nb/Al/Al_xO_x/Al/Nb layers. The electron energy level in the superconductor has a tiny band gap. An incident particle deposits the energy into the superconductor, exited electrons are produced in the superconductor and the number of exited electrons are propotional to the incident energy($N_e = E/1.7\Delta$, where E is a deposited energy and Δ is a band gap energy). The band gap energy of Al and Nb are 0.175 meV and 1.55 meV, respectively. There is a proximitiy effect in the superconducting bi-layer, Al/Nb bi-layer has a band gap between pure Al and pure Nb depending on their thicknesses. Thicknesses of Al and Nb layers are optimized for the operation temperature of 370 mK cooled by the ^{3}He sorption refrigerator. The 1.7Δ of our Nb/Al STJ is approximately 0.5 meV, this value is 1/2000 of silicon band gap. This tiny band-gap allows us to detect infrared single photon. There is an additional current of cooper pairs(supercurrent). The magnetic field applied parallel to the oxidation layer blocks the supercurrent. Figure 3 shows a leak currents of 50 μm$\times$50 μm STJ. It is measured to be less than 250 pA at the bias voltage of 400 μV [4]. This level of leak current already satisfies our requirement.

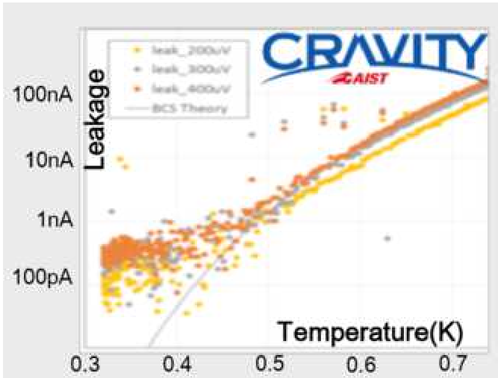

Figure 3: Leak currents of 50 μm$\times$50 μm STJ.

3 FD-SOI based cold amplifier

The STJ response to 465 nm photons is measured with conventional charge amplifier. Typical signal width for 4 photons is $\mathcal{O}(\mu s)$. We cannot detect UV single photon at this experiment. This performance degradation is due to noises(thermal noises, electromagnetic wave absorbtion) and transmission loss in the read out system. An introduction of a cold amplifier is the best solution to minimize the degradation. The JFET is well used to the cold amplifier for STJ. However, the operation temperature of JFET is much higher than the operation temperature of STJ. JAXA/ISAS reported that the FD-SOI MOSFETs shows an excellent performance at liquid helium temperature(4.2 K) and we confirmed that they can be operated at the operation temperature less than 100 mK [5]. The FD-SOI based pre-amplifier amplify the STJ output charge nearby STJ on a temperature stage of 370 mK. Generally, the carrier density in semiconductor decreases at low temperature due to incomplete ionization of the dopants. The carrier mobility increases at low temperature due to decreasing of scattering probability. Hence, the characteristics of FD-SOI MOSFET at cryogenic temperature can be changed compared to the room temperature. The IV characteristics of FD-SOI MOSFETs at cryogenic temperature are measured to prepare the SPICE models for cryogenic temperature. FD-SOI MOSFETs are processed by Lapis semiconductor 0.2 μm process. The four wire sensing method is used to avoid the voltage drop due to the readout wires in refrigerator. Figure 4 left shows Id-Vg characteristics of NMOS source-tie type with W/L = 60/1 μm at Vd=0.9 V. Threshold is increased and transconductance is increased with decreasing temperature. These phenomena implies decreasing the carrier density and increasing the carrier mobility as we expected. Figure 5 right shows Id-Vd characteristics of the same FET at Vg=0.9 V. The non-linear shape is observed at low Vds region and the kink effect is found in high Vds. The cause of the non-linear shape is currently under investigation. Taking into account these effects, FD-SOI MOSFETs are available for read-out circuit of STJ detectors. We will design the charge integration amplifier using special SPICE model. The operational amplifier for this circuit is required to have very fast response(GBW=100 MHz), since the width of STJ signal current is a few μs and STJ has large capacitance(calculated to be $\approx$80fF/μm^2). It must have low power dissipation as compared to the cooling power of refrigerator.

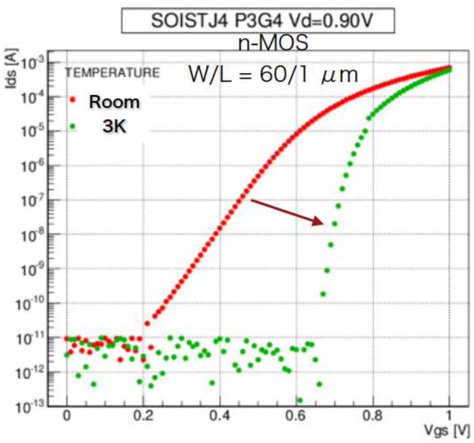

Figure 4: Id-Vg curve of NMOS source-tie type, W/L = 60/1 μm

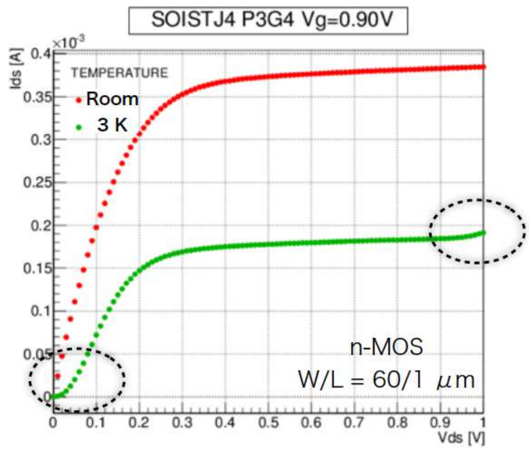

Figure 5: Id-Vd curve of NMOS source-tie type, W/L = 60/1 μm

4 Conclusion

We proposed a new high resolution infrared single photon spectrometer for CνB radiative decay search. The infrared spectrometer has a dispersive element. The STJ is employed to detect infrared single photon. Our STJ achieved the leak current of 250 pA at the bias voltage of 400 μV. The FD-SOI MOSFETs are used to design cold amplifier for STJ readout system. The FD-SOI MOSFETs show excellent performances, non-linear Id-Vd characteristic at low Vd region is under investigation. We will design the charge integration amplifier using FD-SOI MOSFETs.

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