ニュートリノ崩壊光探索に向けた極低温増幅器の開発と現状

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for COBAND Collaboration

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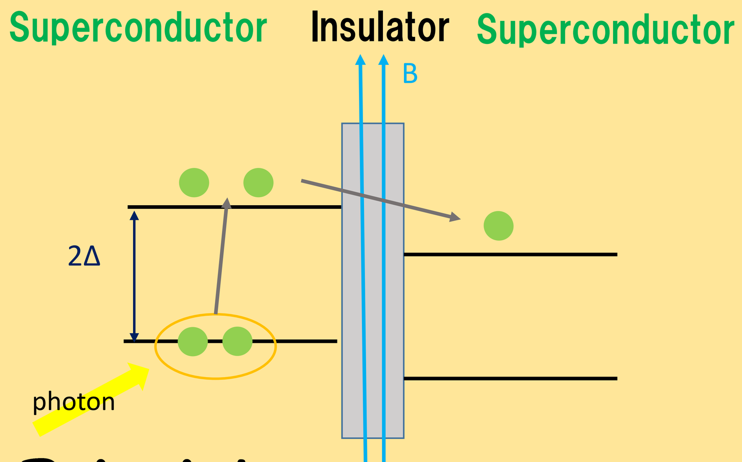
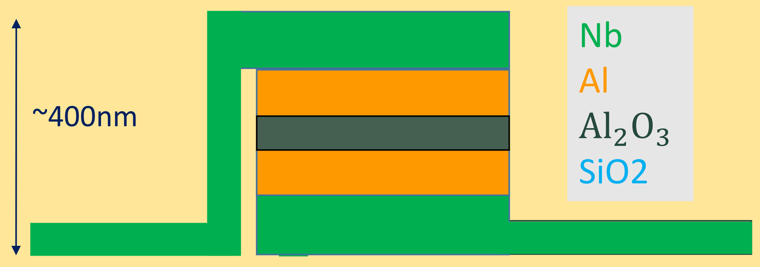
1. Nb/Al Superconducting Tunnel Junction

STJ(Superconducting Tunnel Junction) is a detector for neutrino decay search.
It is composed of Superconductor/Insulator/Superconductor.
Trapped quasi-particles near insulator firm by Al layer cause back tunneling. Nb/Al-STJ has a trapping gain about 10.



Structure of Nb/Al-STJ

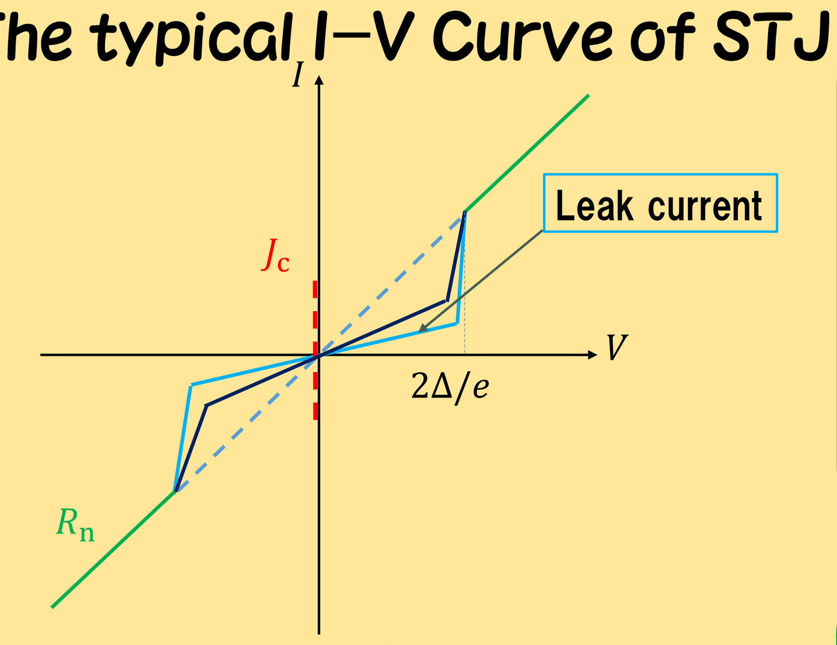


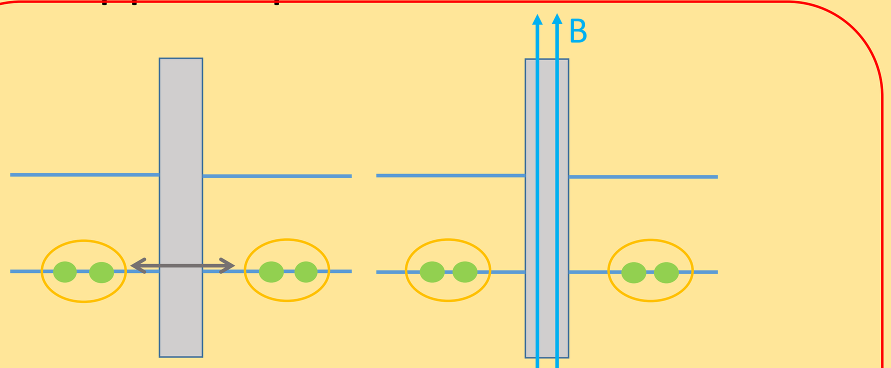
Size : 10um × 10um ~ 200um × 200um

Operating Principle

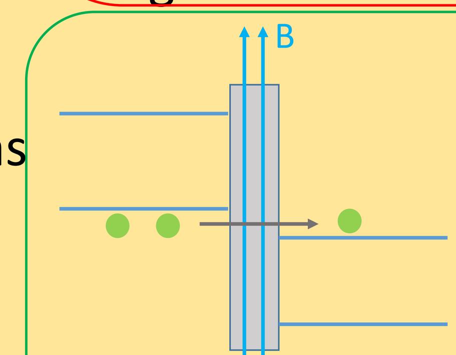
- An incident photon excites cooper pairs to quasi-particles.
- Measure tunnel currents caused by the tunneling quasi-particles as we apply voltages between the lower superconductor and the upper superconductor.

The typical I-V Curve of STJ





Suppress the Josephson currents(J_c) due to cooper pairs by applying the magnetic field.



When bias is larger than 2Δ/e, normal resistance is the same as in the normal conducting state.

When we use this detector, we fix bias voltage to

$$0 < V < |2\Delta/e|.$$

The response signal is so small.

✓ Number of created Quasi-particles

$$N = G_{Al}\frac{E_\gamma}{1.7\Delta}$$

G_{Al} : Trapping Gain(~10)
E_γ : Energy of Incident Photon
Δ : Energy Gap in Superconductor

✓ Energy Resolution

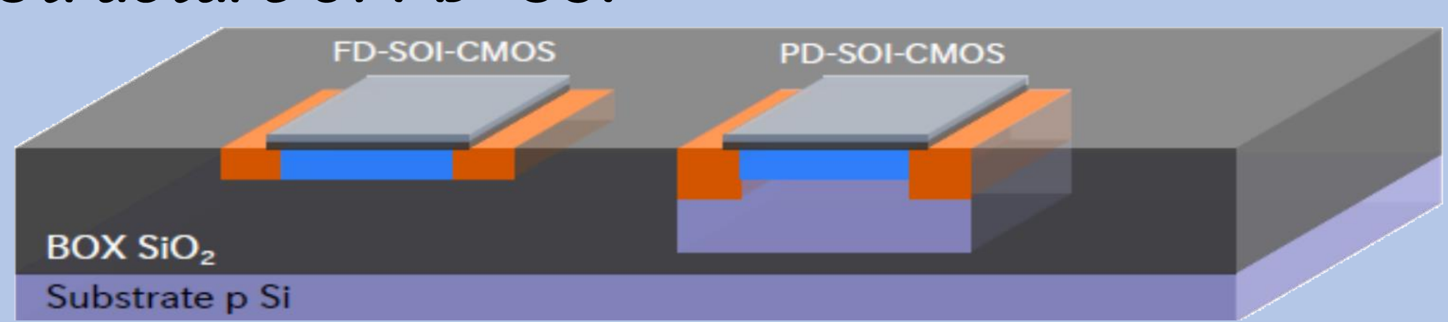
$$\frac{\delta N}{N} = \sqrt{\frac{F}{N}} = \sqrt{\frac{1.7\Delta}{E_\gamma}}$$

F : Fano Factor

	Nb	Al
T_c[K]	9.23	1.12
Δ[meV]	1.550	0.172

2. Fully depleted Silicon-Insulator (FD-SOI)

Structure of FD-SOI



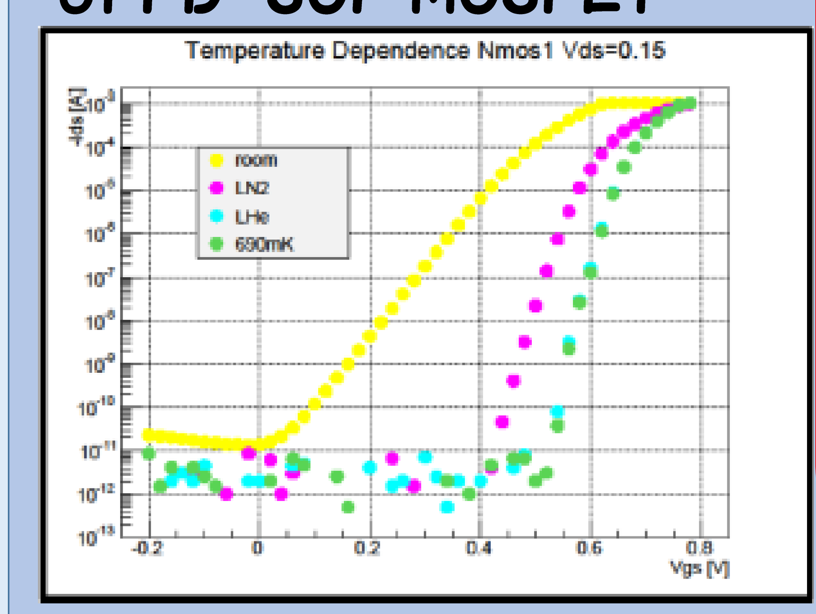
FD-SOI is SOI with the nano-channel layer.

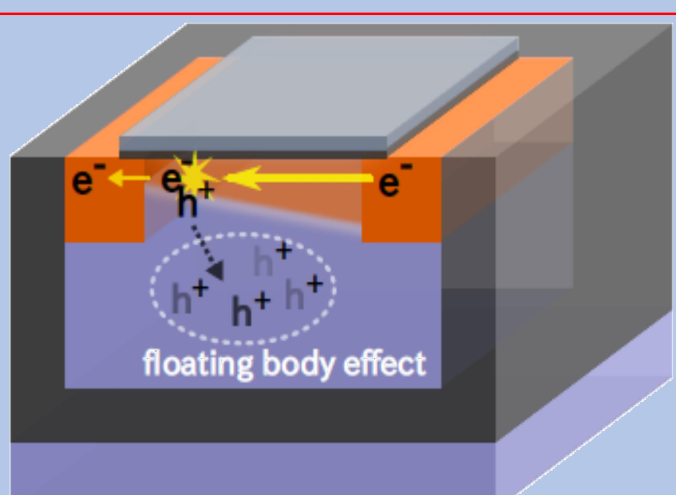
- Very small capacitance between MOSFETs
- Operate in lower power.
- Suppress the floating-pair effect.

A group of JAXA/KEK reports that CMOS FET under FD-SOI process works at a very low temperature (≤4K).

T. Wada et al, Phys. 167, 602 (2012)

The typical Id-Vd curve of FD-SOI-MOSFET





High mobility carrier collide with Si atoms then create electron-hole pairs. The majority carrier left in body, cause floating body effect. The hole is caught by body for carrier-frozen at low temperature.

At low temperature, the threshold voltage of FD-SOI-MOSFET shifts larger. As far as we operate suitable voltage, it does not matter.

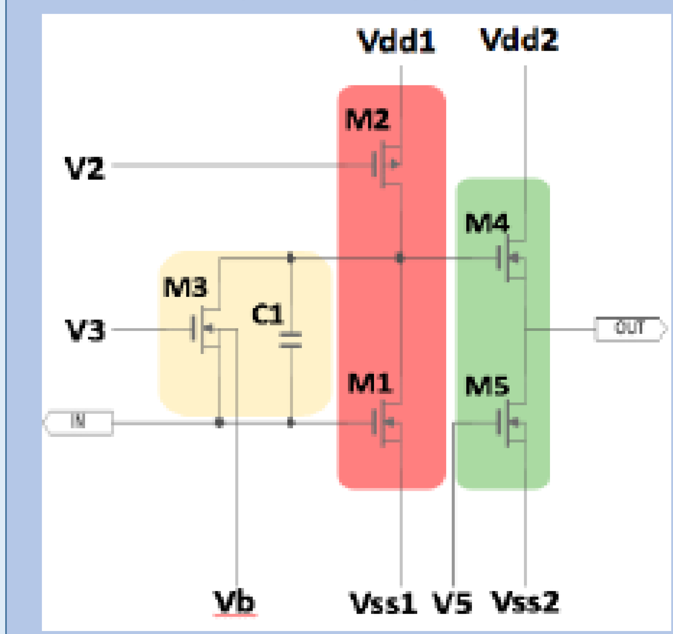
Develop the amplifier using FD-SOI placed near STJ which works at very low temperature and improves the signal-to-noise ratio.

3. Development Cold Amplifier used FD-SOI

Requirement for Cold Amplifier

- Operation at low temperature
  - ✓ Nb/Al-STJ has leakage currents from thermal excitations and imperfect junctions by processing three-layer. Requirement for leakage current in Nb/Al-STJ is smaller than 100pA. Currently, Nb/Al-STJ (20um × 20um) achieve a leakage current of 100pA. We should be able to operate the amplifier at low temperature.
- Low power consumption
  - ✓ Typical cooling power of our refrigerator is 100uW at 300mK, 250mW at 3K.
- Fast response speed
  - ✓ Signal width of Nb/Al-STJ below 10us.

Circuit of SOISTJ4

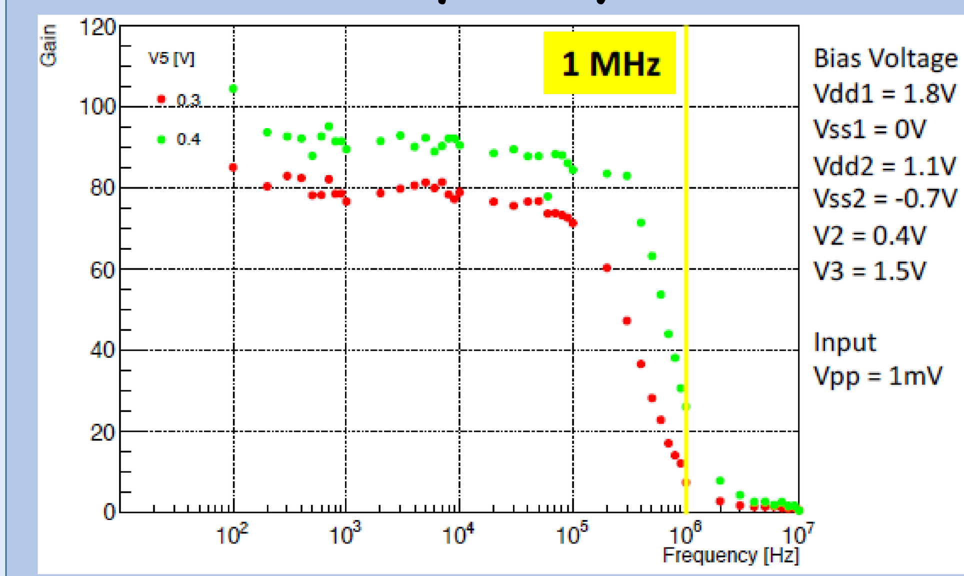


Common source amplifier
Replace a load resistance with MOSFET.

Buffer circuit
Decrease an output impedance.

Feedback circuit
Stabilize a bias of common source.

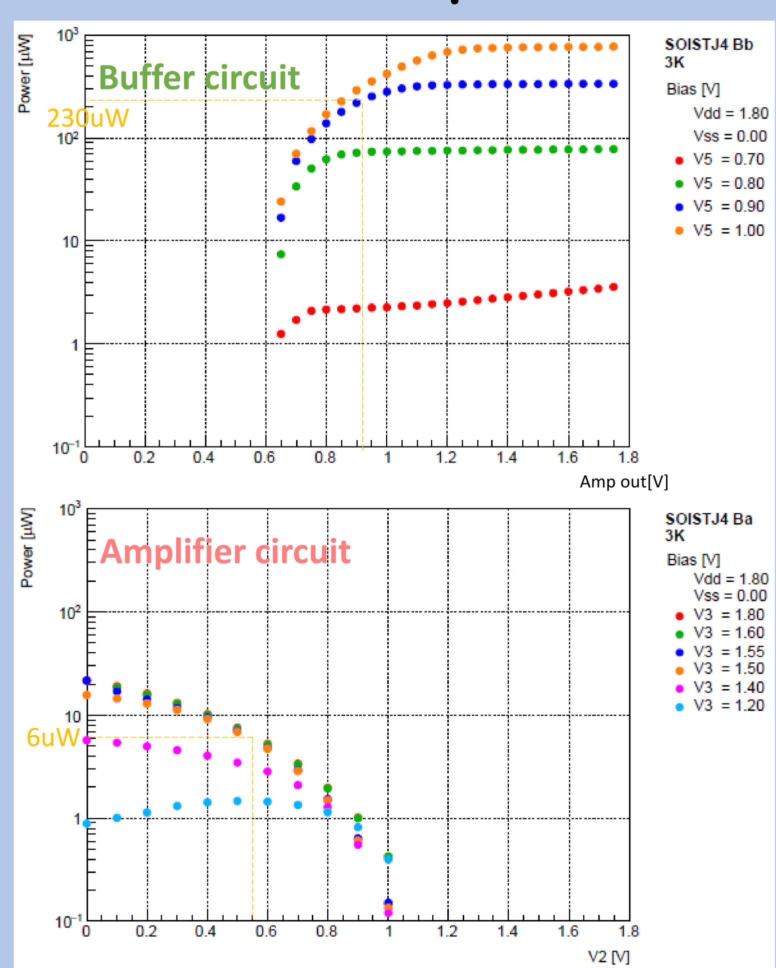
Gain vs. Frequency



At 300mK, SOI amp shows a gain larger than 80 at frequency below 400kHz. A gain is 20 at frequency of 1MHz.

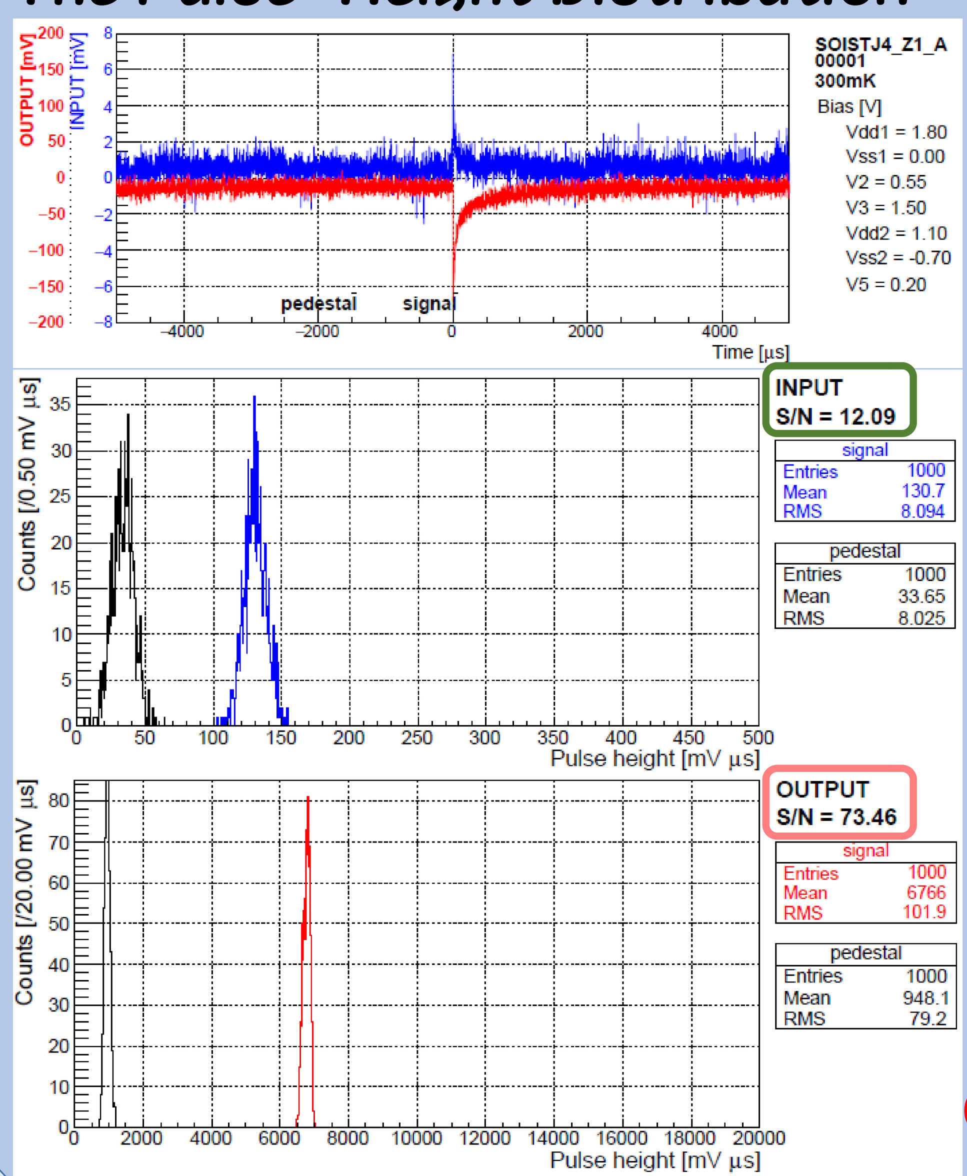
The amplifier is able to work for response signals of STJ.

Power Consumption



Power consumption is about 230uW.
(Vdd2=1.1V, Vss2=-0.7V, V2=0.55V, V3=1.5V and V5=0.2V)

The Pulse-Height Distribution



We consider that the cold amplifier is placed at 3K stage.

✓ Signal-to-noise ratio

$$S/N = \frac{(M_s - M_n)}{RMS_n}$$

M_s : Signal-Height Distribution
M_n : Noise-Height Distribution
RMS_n : Root-Mean-Square of M_n

✓ At room temperature,

$S/N_{INPUT} = 46.26$
$S/N_{OUTPUT} = 250.68$

Where, integration time is 60us.

Circuits of SOISTJ4 improve S/N at low temperature!

4. Summary

We have developed the detector for neutrino decay search.

- Nb/Al-STJ satisfies the leakage current requirement for the COBAND experiment.
- The cold amplifier using FD-SOI MOSFET is being developed.
  - ✓ The cold amplifier was found to work with a gain around 80 up to an signal frequency of 400kHz at 300mK
  - ✓ Power consumption of the cold amplifier exceeds the cooling power at 300mK stage, so we plan to place the amplifier at 3K stage.
  - ✓ Test with an STJ-like input, showed the improvement of the signal-to-noise ratio.