Development of Superconducting Tunnel Junction(STJ) Photon Detector on SOI Preamplifier Board to Search for Radiative Decays of Cosmic Neutrino Background

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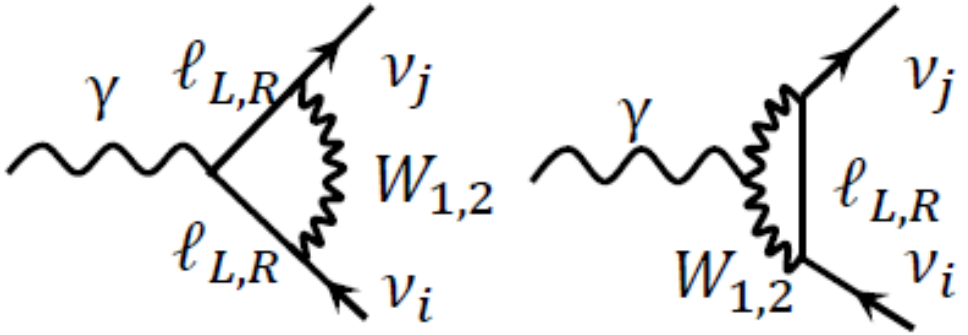
Outline

- Motivation(Search for Neutrino Radiative Decay)
- Introduction of Superconducting Tunnel Junction(STJ)
- STJ on Silicon-on-Insulator Preamplifier-board(SOI-STJ)
- Current Status on development of SOI-STJ
- Future Plan
- Summary

Motivation

Neutrino Mass Measurement

- We know that neutrinos have small mass but neutrino mass itself have not been measured.
- Aiming at measuring neutrino mass itself with Neutrino Radiative Decay.



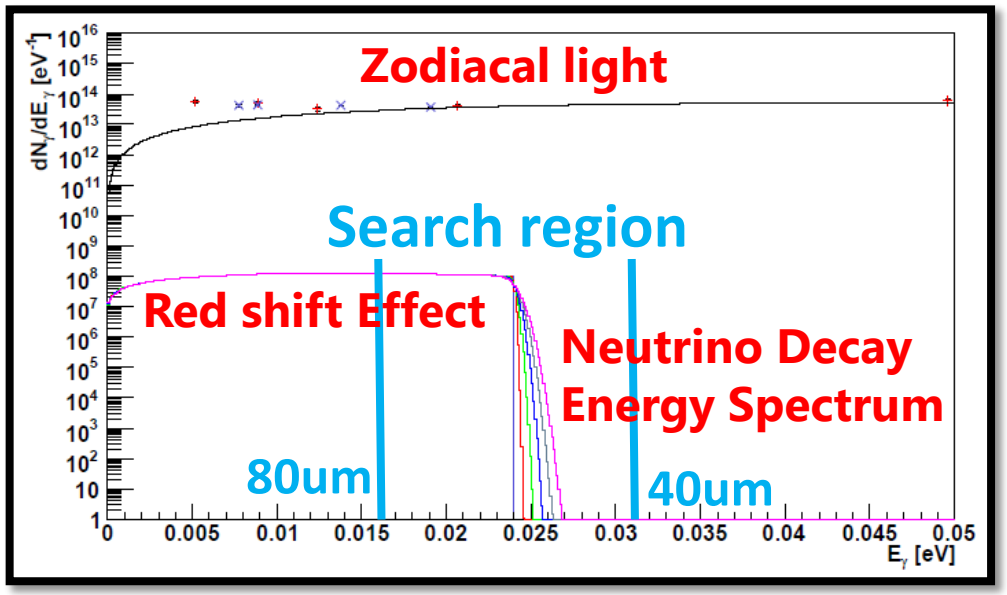
$$E_\gamma = \frac{m_3^2 - m_2^2}{2m_3}$$

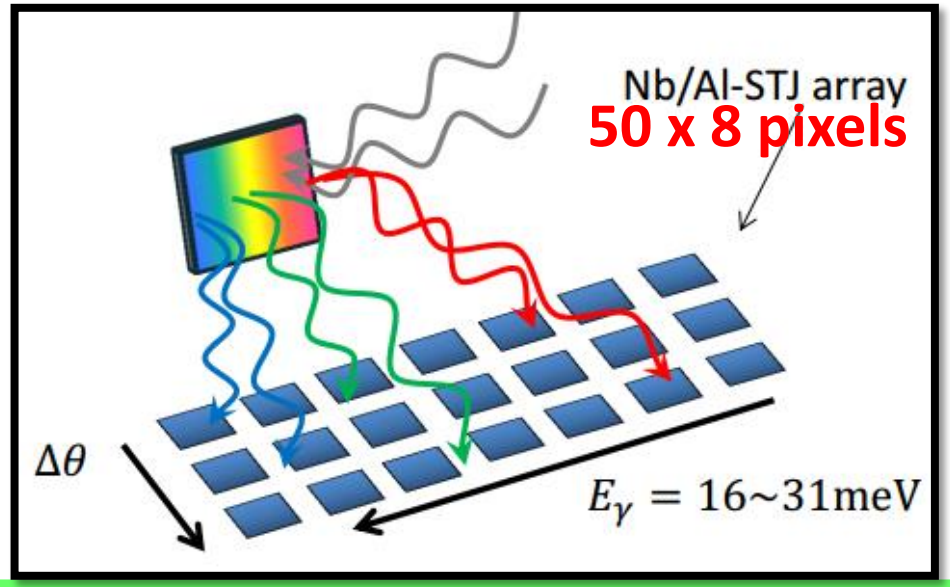
Lifetime of Neutrino($\nu_3 \rightarrow \nu_{1,2} + \gamma$)

- 10^{43} years in SM expectation, $\tau \gtrsim O(10^{17})$ years in left-right symmetric model ($SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$)
- Present limit is 3 x 10^{12} years (AKARI).
- We will use Cosmic Neutrino Background as neutrino source for Neutrino Decay.

Requirements for the Detector

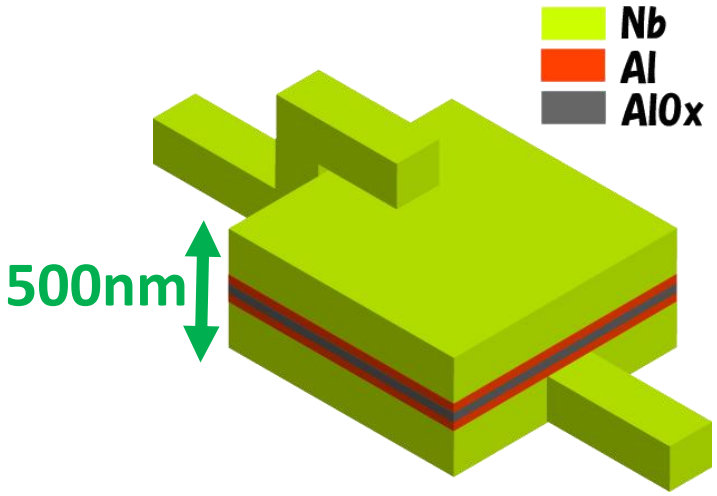
- Expected energy of photon in neutrino radiative decay is $E_\gamma = 25\ \mathrm{meV}(m_3 = 50\ \mathrm{meV}$ is assumed).
- In this region, biggest background is zodiacal light.
- To detect the neutrino radiative decay significantly in CIB, We need the photon detector which has **2% energy resolution for 25meV(50um)**.





- Nb/Al-STJ photon detector (50 x 8 pixels) with grating is a candidate for our experiment.
- Aiming at improving the current experimental lower limit of the neutrino lifetime by 2 order in rocket experiment: $\tau(\nu_3)$>O(10^{14} years)

STJ Photon Detector



Number of Quasi-particles in Nb/Al-STJ

$$N_q = G_{Al} E_0 / 1.7\Delta$$

G_{Al} : Trapping Gain In Al(~10)
E_0 : Photon Energy
Δ : E-Gap in superconductor

For 25meV single photon

$$N_q = 10 \frac{25\ meV}{1.7 * 1.550\ meV} = 95\ e$$

What's STJ(Superconducting Tunnel Junction) ??

STJ is a Josephson Junction composed of **Superconductor / Insulator / Superconductor.**

Principle of Operation

1. Photon absorbed in superconducting layers of STJ during applying magnetic field.
2. Excites cooper pair into quasi-particles according to absorbed energy.
3. Observe tunneling current due to quasi-particles through the insulator.

	Si	Nb	Al
Tc[K]		9.23	1.20
Δ[meV]	1100	1.550	0.172

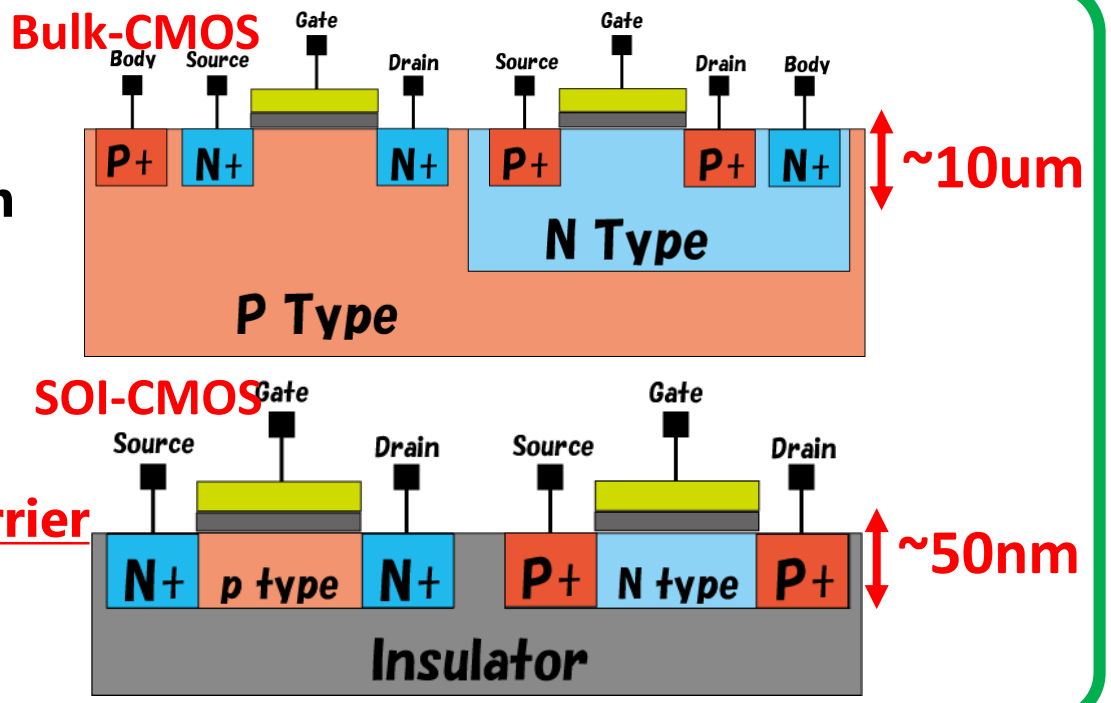
Development of cold preamplifier

- **Current Status of Development for Nb/Al-STJ(if you want to know detail, please see Yuji TAKEUCHI's slides- Ⅱ.c Neutrino session 12:00-).**
  - We haven't succeeded in detecting a far-infrared single photon yet due to **readout noise(thermal noise and cable noise)**.
  - Need to adopt the preamplifier operated at ultra-low-temperature.
  - FD-SOI device was proved to operate at 4K by a JAXA/KEK group(AIPC 1185,286-289(2009)).

Silicon on Insulator(SOI)

- **Processing LSI on SiO_2 Insulator.**
- **Very Small Parasitic Capacitance due to Separation between MOSFETs with insulator(Not Depletion).**
  - **Low-Power to be Operated(400 uW)**
  - **High Speed(1 MHz)**
  - **Good at Large Scale Integration**
  - **Suppression of charge-up by high mobility carrier due to thin depletion layer(~50nm).**

➡ **Apply this to readout of STJ signal !**

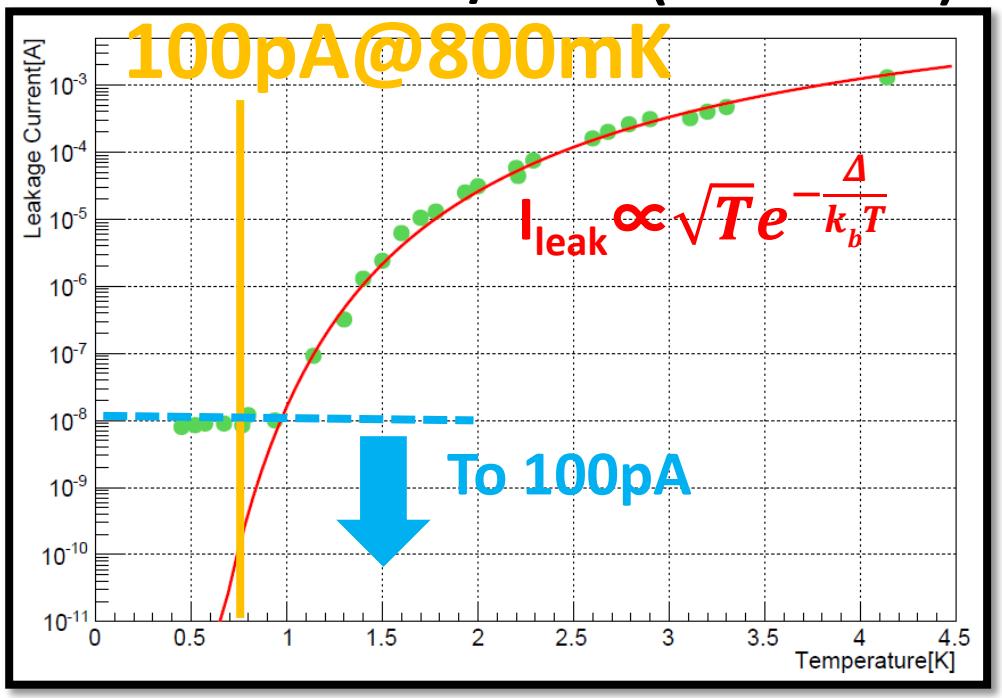


Requirement for the amplifier of STJ readout.

Operation at ultra-low temperature

- Requirement for leakage current of Nb/Al-STJ is below 100pA.
  But practically, leakage current is caused by…
  - **Pinhole(constant) across the insulator**
    - **We can expect to reduce it by using smaller one.**
  - **Thermal excitation($\propto \sqrt{T}e^{-\frac{\Delta}{k_b T}}$)**
    - **-We need to make cooler to 800mK.**

Temperature Dependence of Dark Current with Nb/Al-STJ(10000um²)



1. Operating below 800mK

3He sorption is better

Low power consumption

- Typical cooling power of our refrigerator is 400uW.

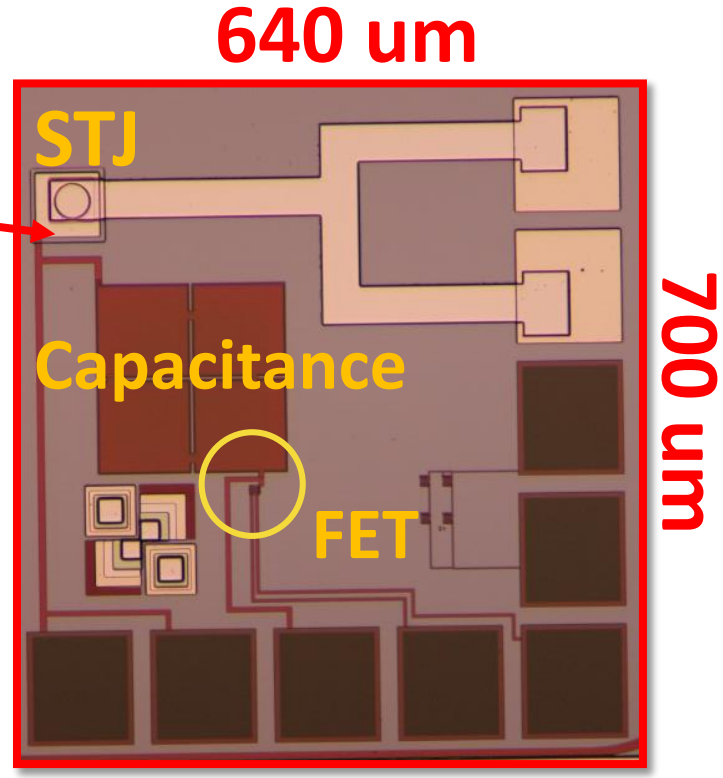
2. Power consumption in the amplifier is as low as possible.

Speed

- We think that integration region of charge is from 1uS to 4uS.

3. amplifying up to 1MHz is sufficiently good to apply it.

SOI-STJ



What's SOI-STJ ?

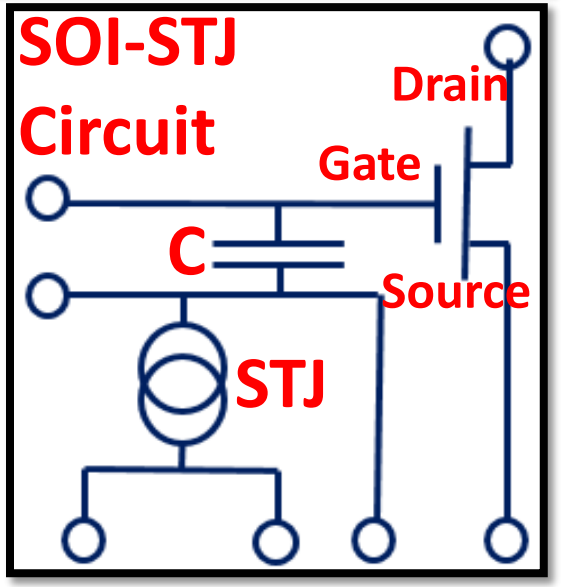
Processing Nb/Al-STJ on SOI preamplifier board directly.

- **Expected good signal-to-noise ratio.**
- **Potential for expansion of multi-pixel device**

The first prototype of SOI-STJ

We tested the Nb/Al-STJ on SOI wafer which only include MOSFET to answer the following questions:

- SOI-FET has no damage by processing STJ ?
- Quality of Nb/Al-STJ can be good on SOI wafer ?

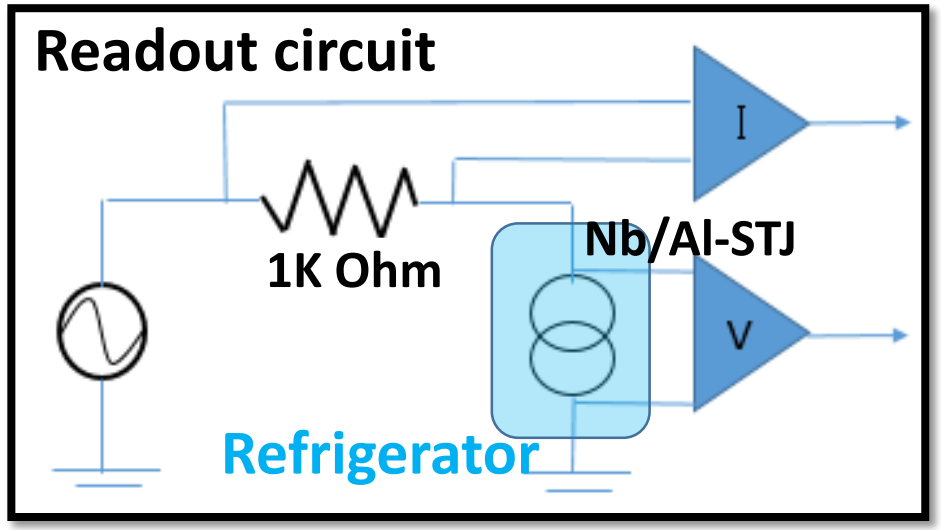


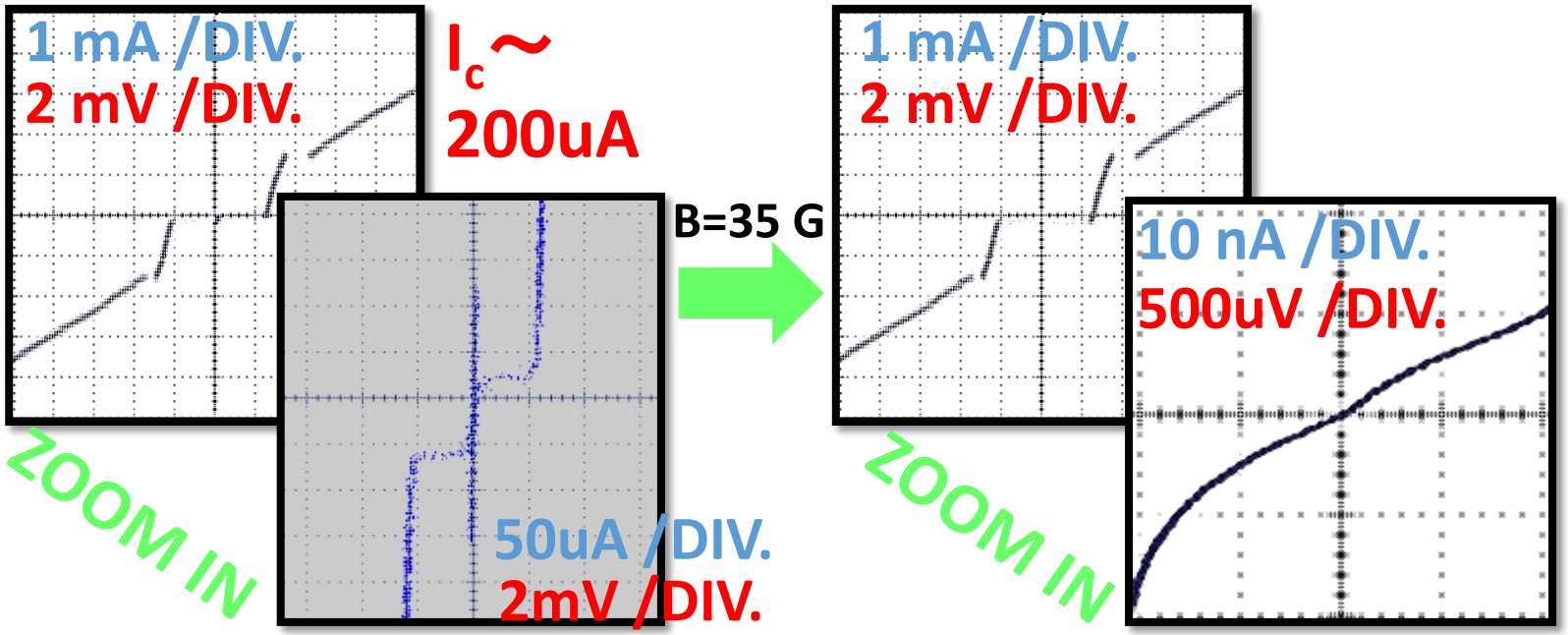
Nb/Al-STJ can be processed on SOI wafer perfectly ?

We have measured I-V curve of Nb/Al-STJ (50um x 50um junction) processed on SOI wafer

At **700mK** with dilution refrigerator.

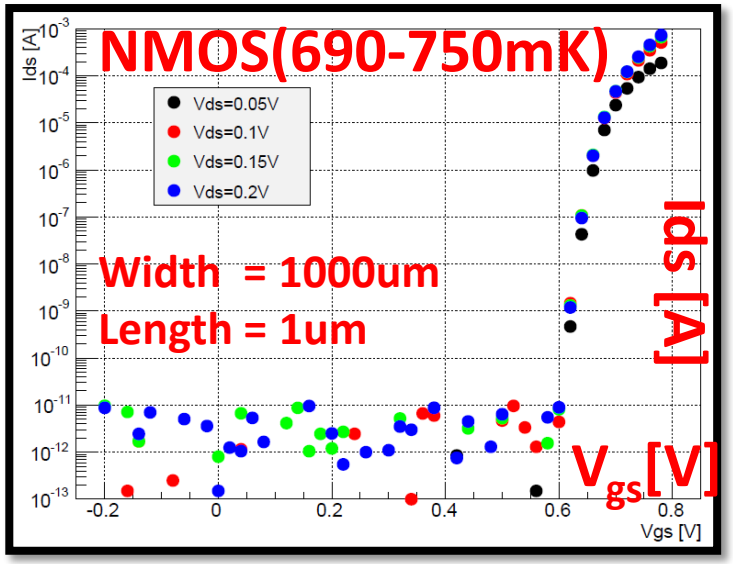
- **We have seen the distinctive I-V curve of Josephson Junction !**

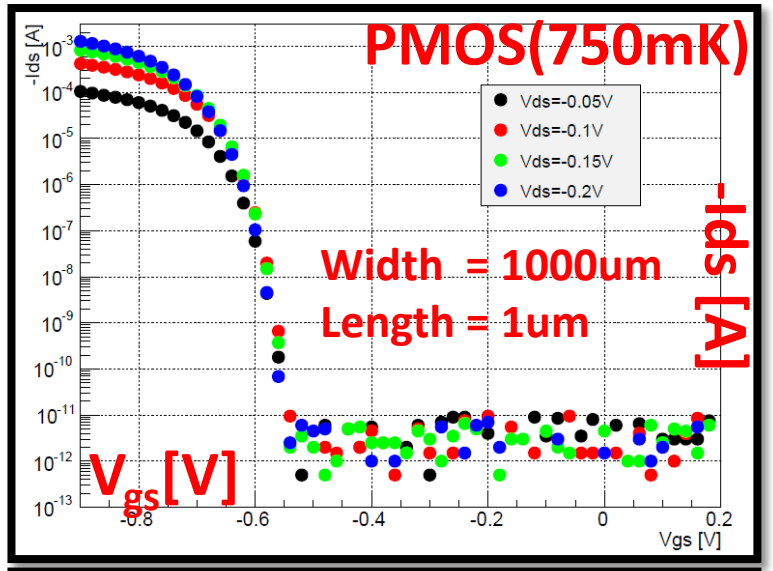


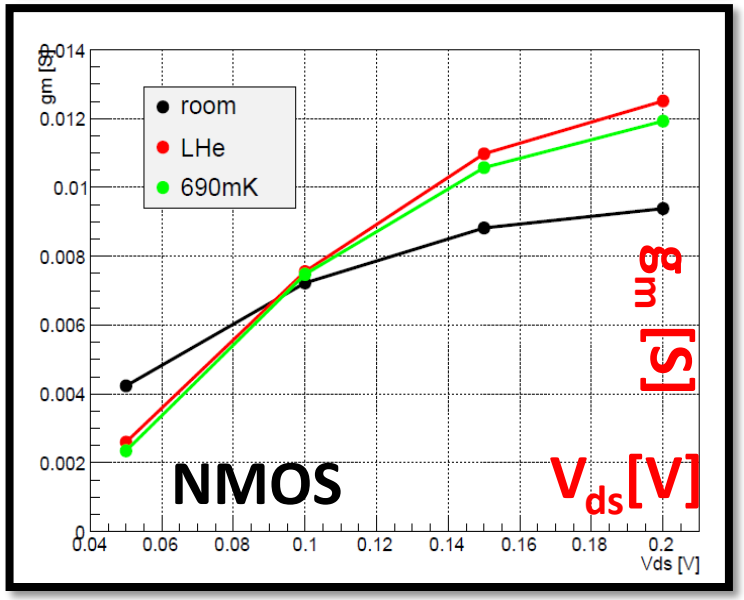


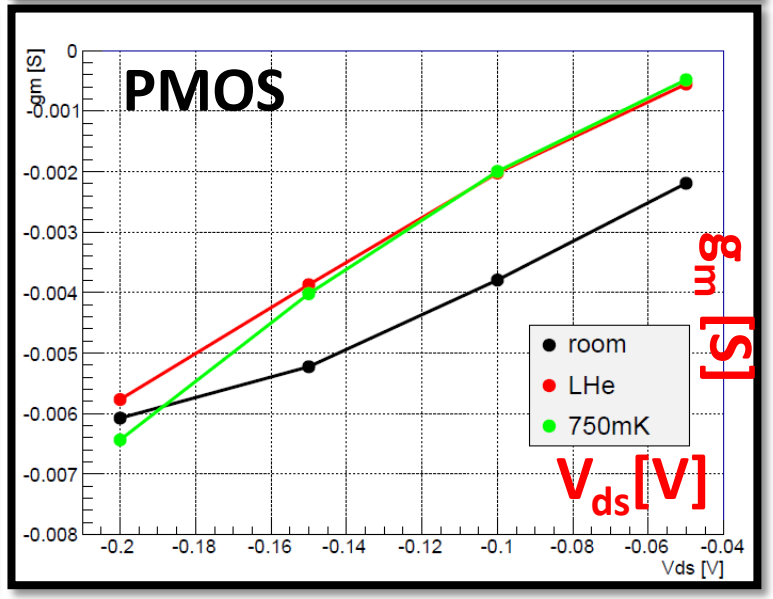
- Leak current @ 0.5mV is **6nA**.
  It's almost same as our best record of normal Nb/Al-STJ(100um x 100um) 10nA.
- Quality Factor ($R_{dynamic}/R_{normal}$)
  On Si wafer : 5×10^5
  On SOI wafer : 3×10^5

1. SOIFET can be operated below 800mK ?









I-V curve of SOIFETs after processing Nb/Al-STJ.

- Both of NMOS and PMOS could be operated below 800mK.
- Trans-conductance "g_m" was not varied drastically for each temperature at operation voltage(0.2V).

We can use these as Preamplifier for STJ signal at ultra-low temperature.

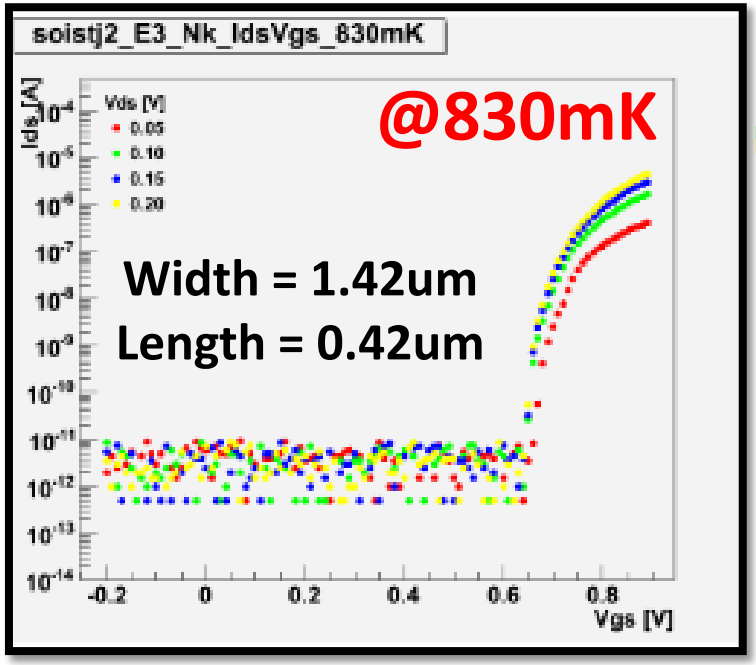
Excellent performance !!

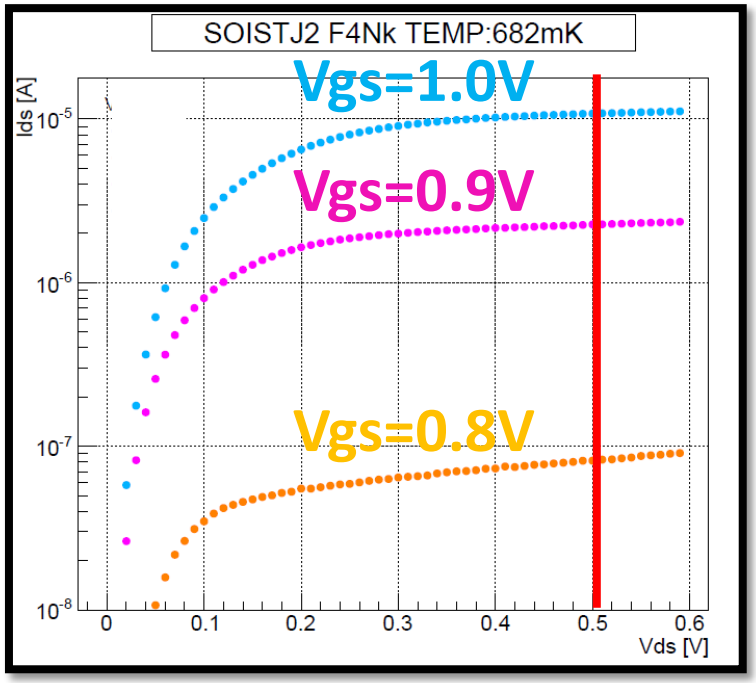
2. Power Consumption of SOIFET

- Bias voltage of SOI-FET in saturation region(red line at right figure) : **0.5 V**
- Current (I_{ds})of FET in saturation region at Vgs = 0.8V : **0.09 uA**

Power consumption = **0.5 V** × **0.09 uA**

= **45 nW/FET(W/L=3.4)**

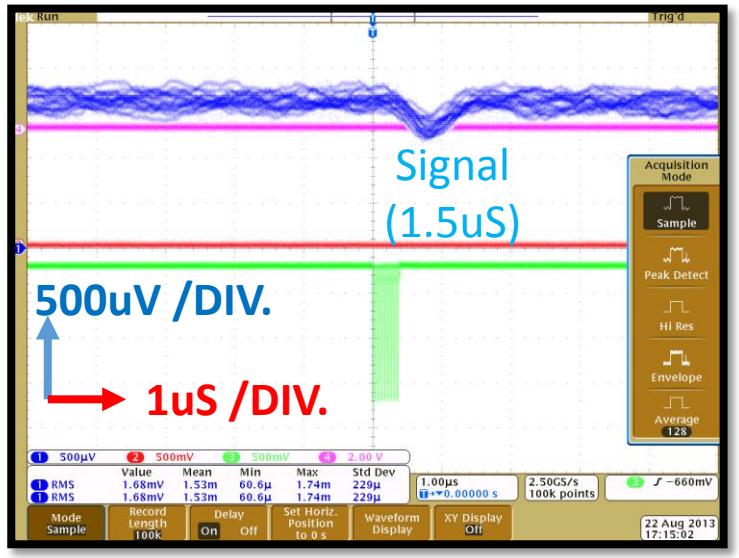




- We need to calculate the thermal model in rocket experiment firstly.

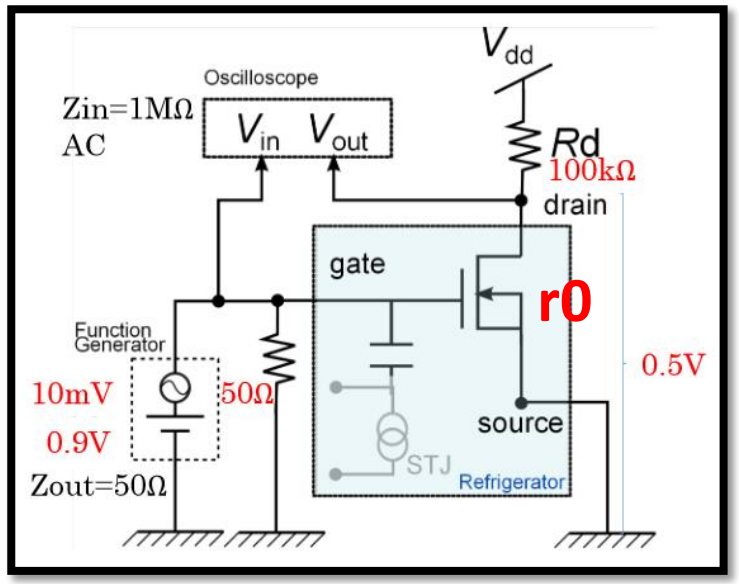
- We investigate the possibility of using it around the threshold voltage(lower power and higher gain are expected, but lower speed).

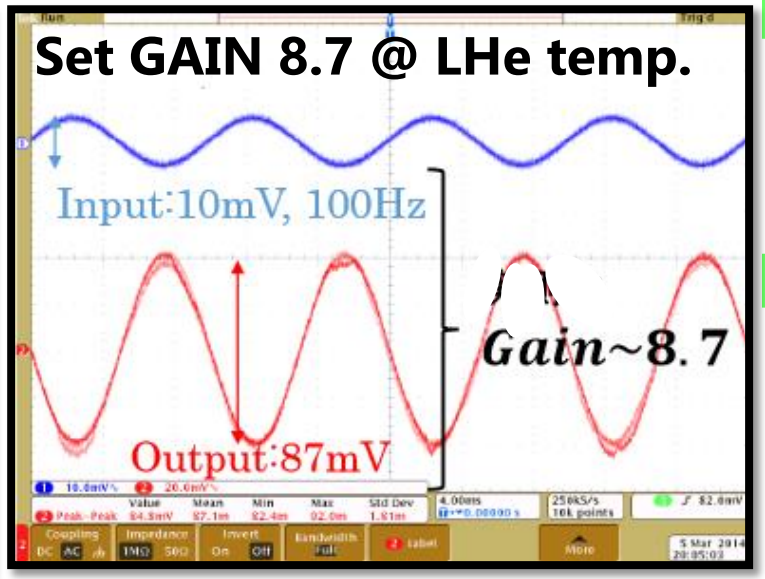
3. Frequency dependence of SOIFET



- We observed the signal of Nb/Al-STJ processed on SOI board to 465nm laser pulse.
- The width of the signal of Nb/Al-STJ is about **1 uS**.

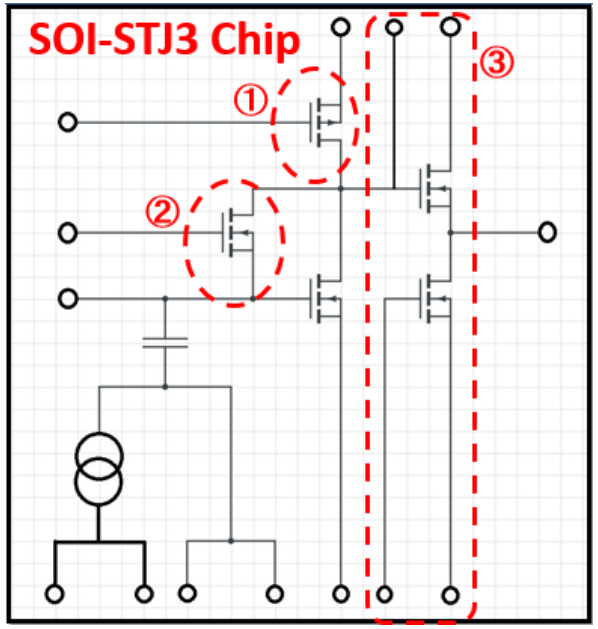
Our requirement for the amplifier is operation above 1 MHz in order to best S/N.

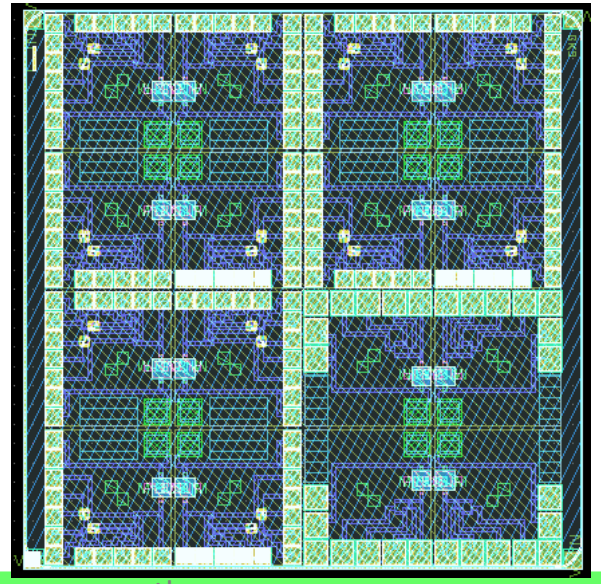




- We Checked the behavior of SOI-FET as the preamplifier.
- But we can not measure the gain at high frequency due to too large output impedance.

Future Plans





- **We are updating the SOI-STJ schematic for amplification of the Nb/Al-STJ signal.**

  Designed the ratio (W/L) so that the operation power is below 120uW.

1. **Replace the resistance to SOI-FET that we use as current source.**
2. **Employ the Feedback between drain and gate to apply stable bias voltage**
3. **Add the follower to reduce the Output Impedance.**

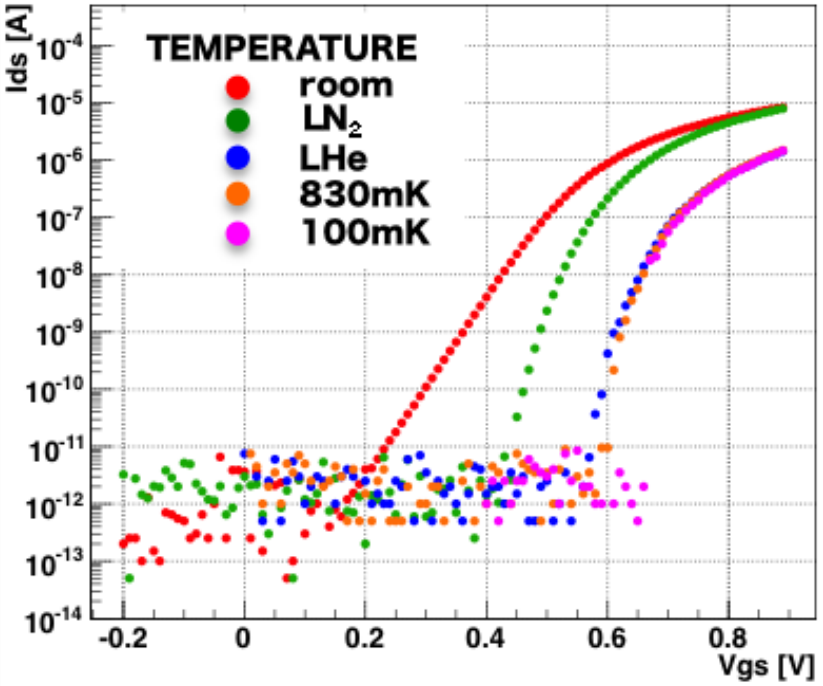
In current status, We will measure the response to laser pulse with renewed SOI-STJ soon.

Summary

- SOI-STJ photon detector is under development for detecting far-infrared single photon for neutrino mass measurement.
- We processed Nb/Al-STJ on SOI-FET board and confirmed the following performances.

- **SOIFET has no damage by processing Nb/Al-STJ.**
- **Nb/Al-STJ is also operated normally.**
- **SOIFET can be operated below 800mK.**

***For your information, we also confirmed that SOIFET can be operated at 100mK.**

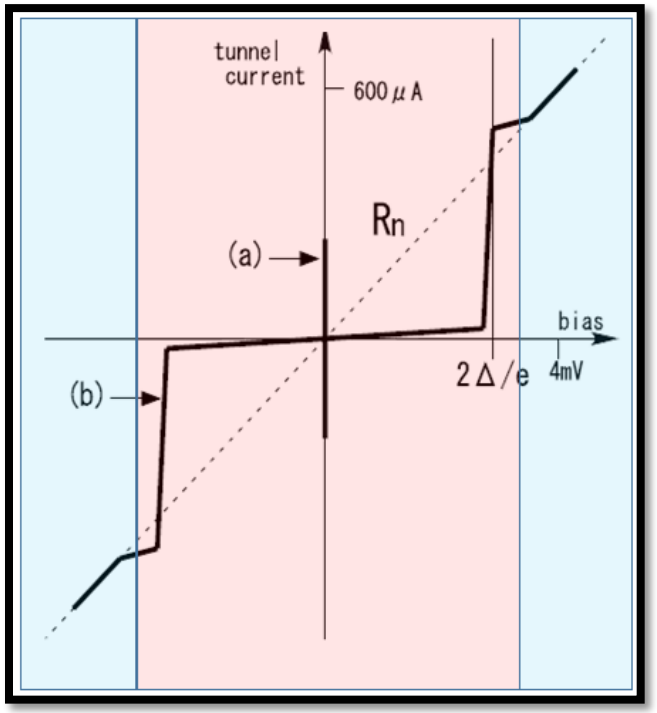


Back Up Slides

The I-V curve of Josephson junction

How can we check the performance of STJ??

- Josephson Junction has distinctive I-V curve.
  - **Blue region**
    - **Cooper pairs can go through directly the other electrode due to larger bias than gap energy.**
  - **Red region**
    - **The cooper pair tunneling Current is seen at V = 0V.**
    - **This is suppressed during applying Magnetic fields.**



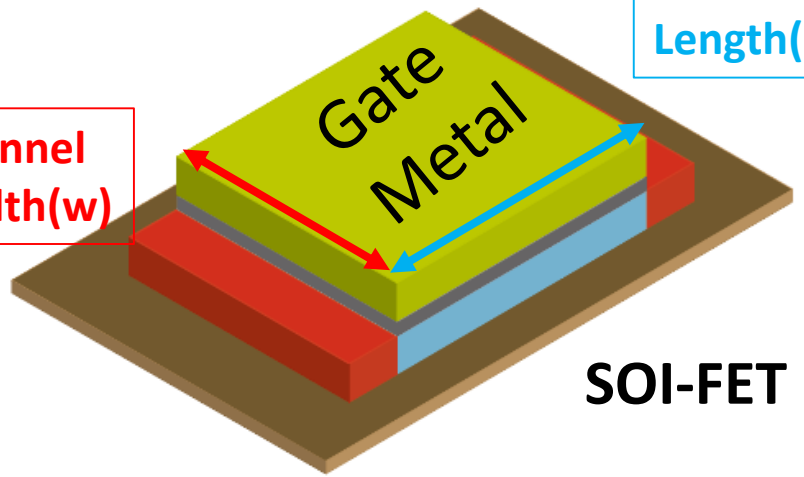
- The leakage current at operation voltage(0.5mV) deteriorate of energy resolution.
  - To discriminate signal from leakage current fluctuation, **the leak current of the Nb/Al-STJ should be below 100pA(Our best sample has 10nA).**

Trapping Gain

STJ Back tunneling

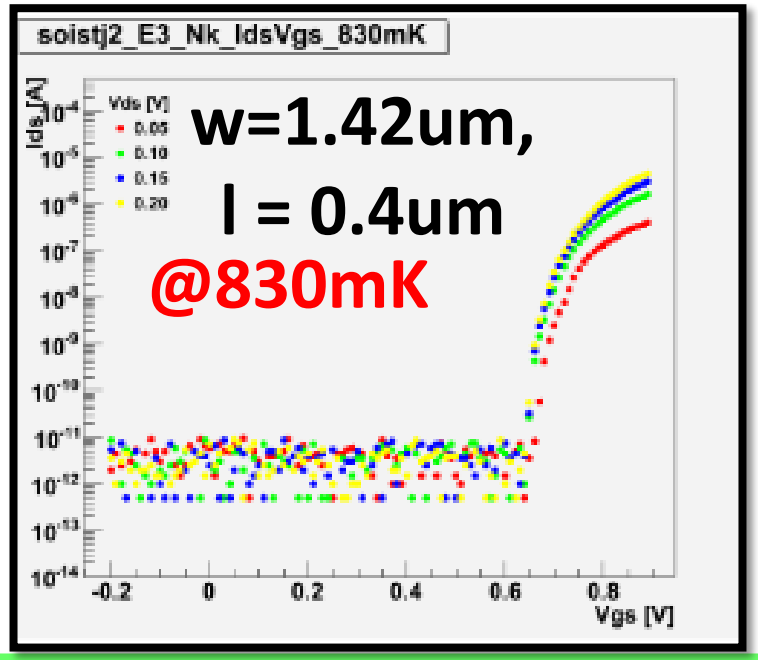
- When quasi-particle that is created around insulator go through the insulator layer, then quasi-particle break cooper pair in opposite layer and make cooper pair with one of quasi-particles.

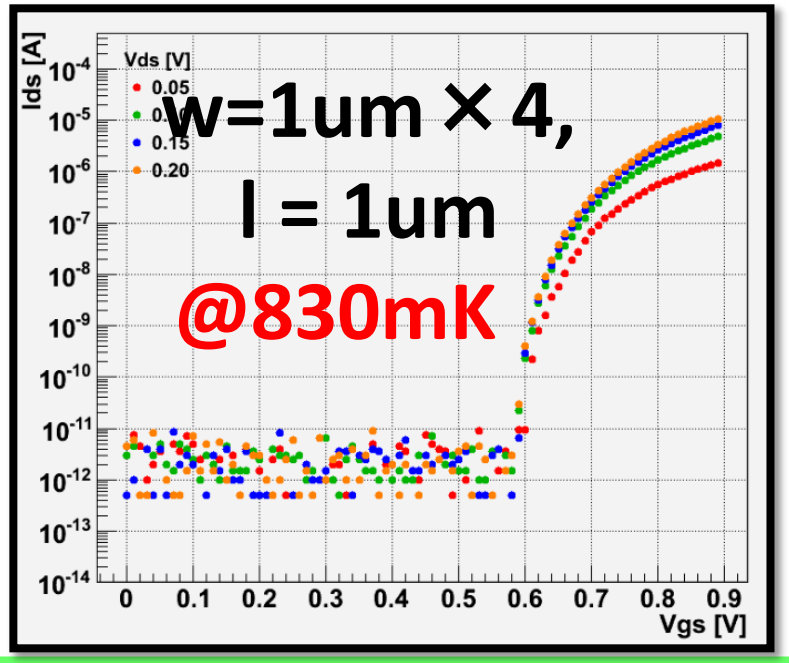
I-V curve of SOIFET @ ultra-low temperature

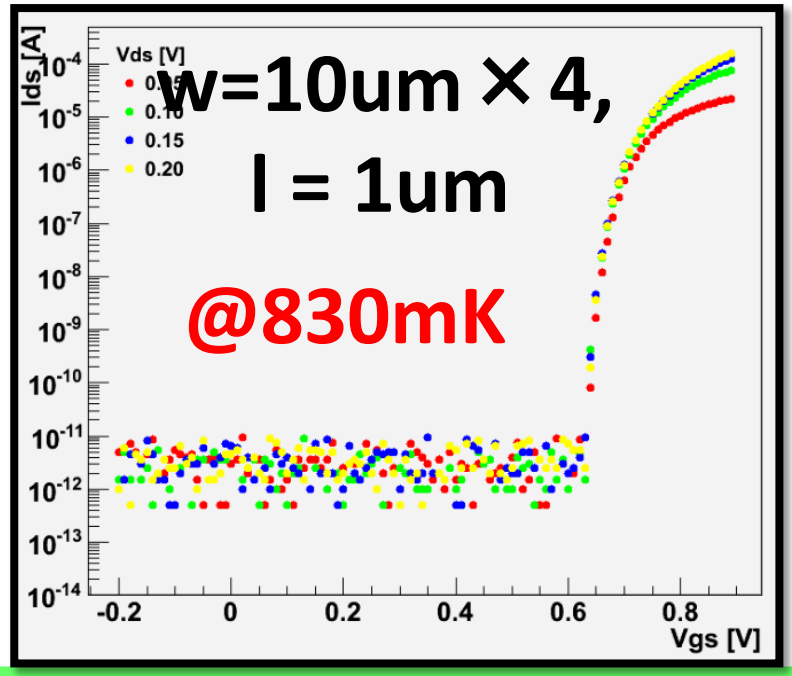


SOI-FET

We can see the I-V curve for each W/L value.







Requirement for leakage current of Nb/Al-STJ

When far-infrared single photon incident to the Nb/Al-STJ, Number of created quasi-particle in STJ is around **100e**(assuming Gal = 10).

We want to separate between the signal and pedestal (3 sigma). so requirement for fluctuation of the leakage current of STJ is follow.

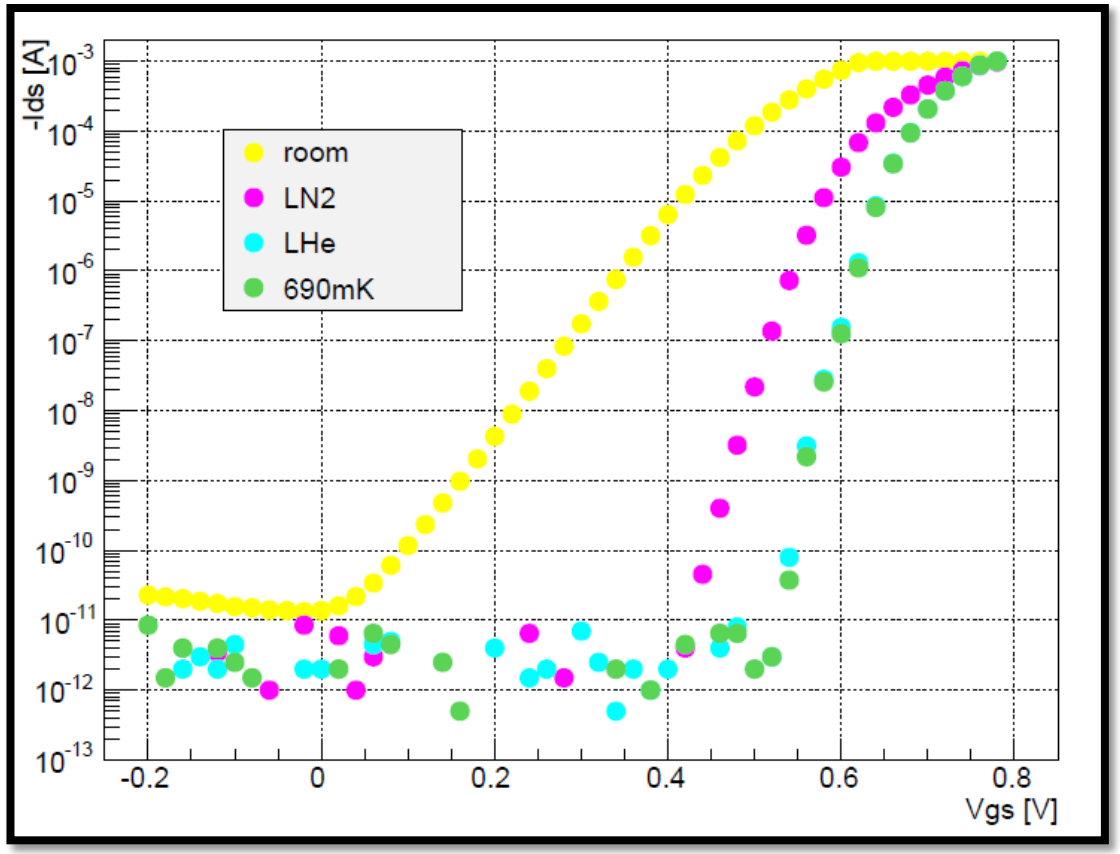
$$\delta N_{qleak} = 33 \text{ e}$$

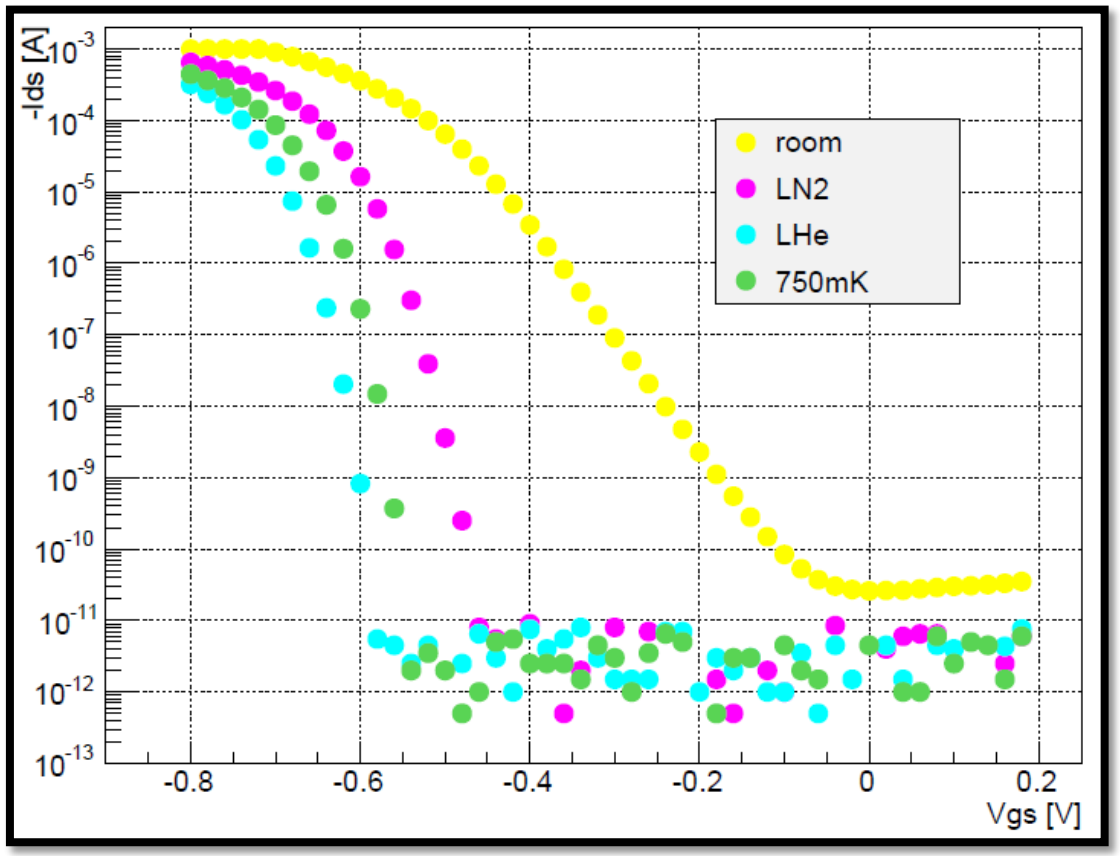
If we assume that integration width is 1.5 uS, our requirement for the leakage current is…

$$N_{qleak} = 1089 \text{ e}$$

$$I_{leak} = \frac{1089 \times 1.6 \times 10^{-19}}{1.5 \times 10^{-6}} = 108[pA]$$

Temperature Dependence of I-V curve





Threshold voltage is changed. But the other properties are almost unchanged.

Energy resolution of Nb/Al-STJ

Energy Resolution of STJ

$$\delta E_{FWHM} = 2.35\sqrt{(1.7\Delta)FE}$$

F : Fano Factor

Δ :Gap energy

E : Photon energy

For 25meV single photon

$$\frac{\delta E_{FWHM}}{E} = 2.35\sqrt{\frac{(1.7\Delta)FE}{E}} = 22\%$$