R&D of cryogenic SOI amplifier for COBAND experiment

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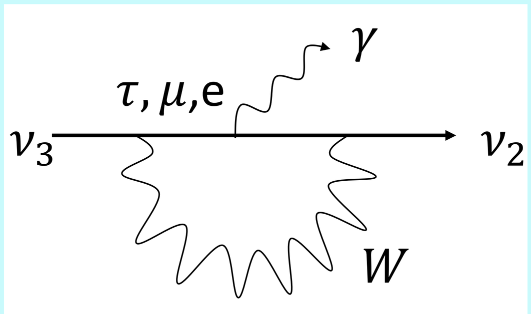
1. COBAND Experiment

COsmic BAckground Neutrino Decay search experiment

- The purpose of the experiment is to determine neutrino masses by measuring the neutrino decay photon.
- Neutrino has a long lifetime (T>O(10^{12}) years : COBE+AKARI measurement). We use the cosmic background neutrino.
- The emitted photon energy from the diagram is



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

$|\Delta m_{32}^2| = (2.44 \pm 0.06) \times 10^{-3}\mathrm{eV}^2$
$\Delta m_{21}^2 = (7.52 \pm 0.18) \times 10^{-5}\mathrm{eV}^2$
by neutrino oscillation experiments.

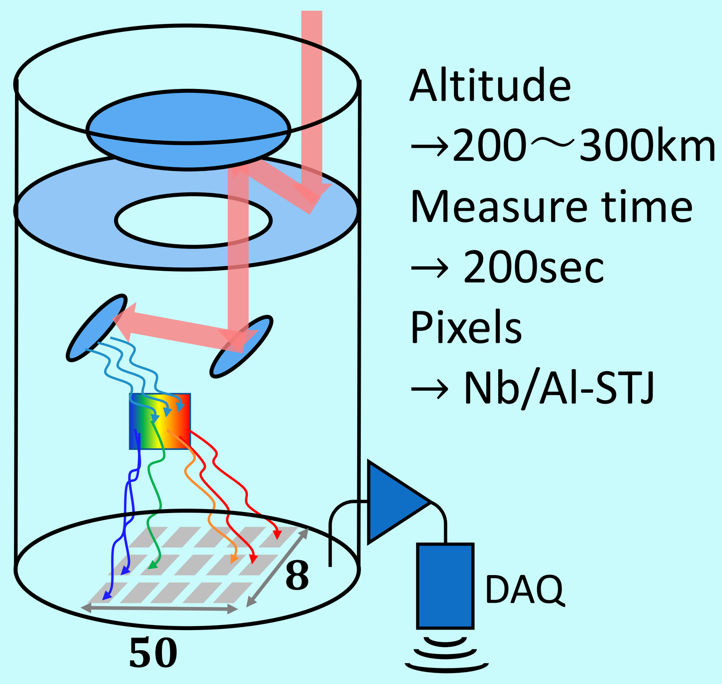
It is expected

$$E_\gamma \sim 25\mathrm{meV}\ (\lambda_\gamma = 50\mu\mathrm{m})$$

at $m_3 = 50\mathrm{meV}$. We measure the energy by using the superconducting tunnel junction.

Rocket experiment

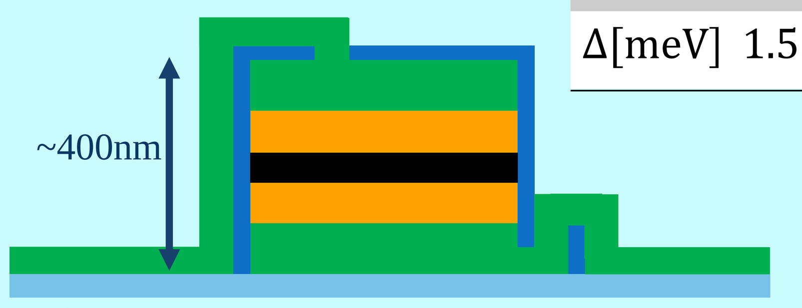
- Aiming at a sensitivity to 10^{14} years for the neutrino lifetime
- The diffraction grating covers $\lambda = 40 - 80\mu\mathrm{m}$.
- We count number of photons inputted the 50 × 8 array of pixels respectively and measure the energy spectrum.



Altitude
→200〜300km
Measure time
→ 200sec
Pixels
→ Nb/Al-STJ

Nb/Al-STJ

	Nb	Al
T_c[K]	9.23	1.12
Δ[meV]	1.55	0.17



Size : $10\mu\mathrm{m} \times 10\mu\mathrm{m}$ ~ $200\mu\mathrm{m} \times 200\mu\mathrm{m}$

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

✓ Number of created Quasi-particles

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

✓ Energy Resolution

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

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

2. Development of Cryogenic SOI Amplifier

Introduction of Cryogenic Amplifier

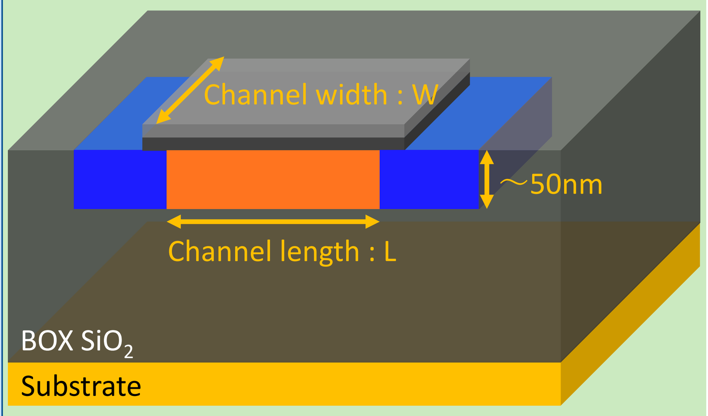
- Nb/Al-STJ has leakage currents from thermal excitations and imperfect junctions by processing three-layer. Requirement for leakage current in Nb/Al-STJ is smaller than 100pA and the requirement is already achieved.
- However we have not been able to detect the far-inferred single photon yet, because of the large noise from the refrigerator's readout line. We consider amplifying the STJ signal by cryogenic amplifier placed near STJs.

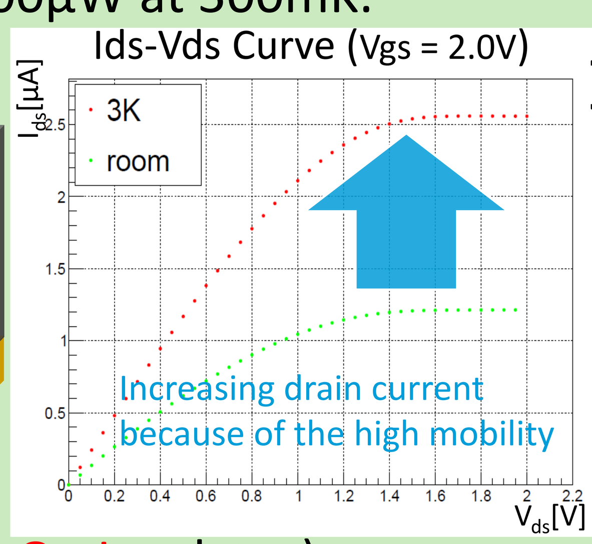
Requirement for Cryogenic Amplifier

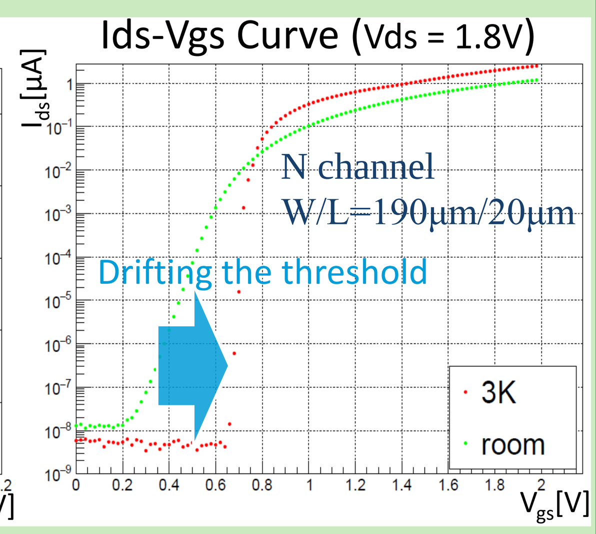
- Operation at low temperature (<3K)
- Fast response speed (width of signal <10μs)
- Low power consumption
  - ✓ Cooling power of our refrigerator are 250mW at 4.2K and 100μW at 300mK.

STJ size	I_{leak} @300mK
50μm×50μm	224±29pA
20μm×20μm	39±13pA
10μm×10μm	14±7pA

FD-SOI MOSFET







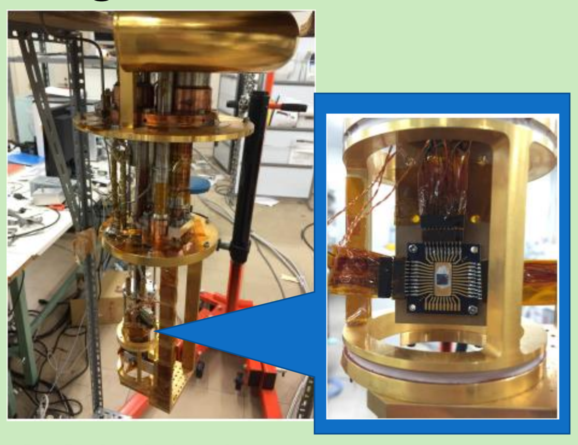
FD-SOI(Fully Depleted-Silicon On Insulator) MOSFET is a transistor under SOI process with a nano-channel layer.
✓ Low power consumption
✓ Suppress charge-up of the body
A group of JAXA/ISAS reported working the FD-SOI MOSFET at 4K.
※ T. Wada et al., J. Low. Temp. Phys. 167, (2012) 602

At low temperature, the threshold voltage of FD-SOI-MOSFET shifts larger and I_{ds} increase. As far as we operate suitable voltage, it does not matter. We develop cryogenic amplifier using FD-SOI MOSFET.

3. Test of the Cryogenic Amplifier

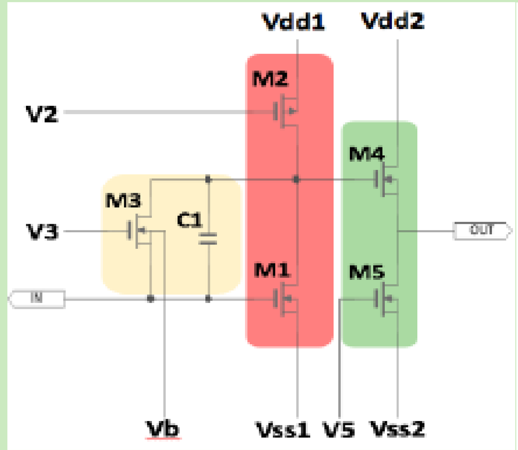
³He Sorption Refrigerator

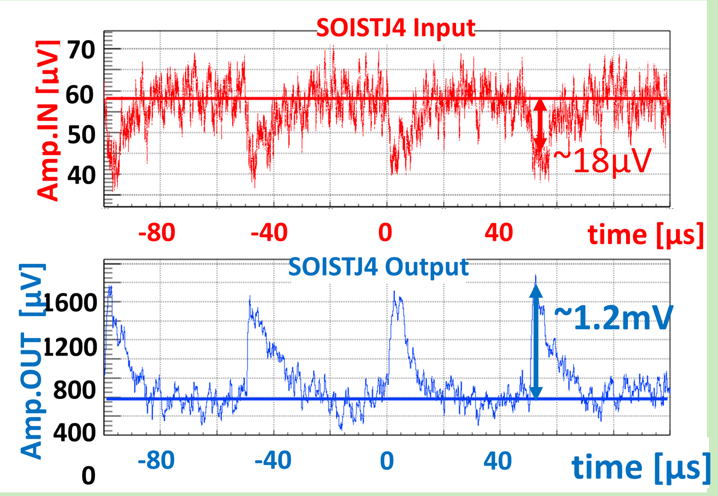
Conducting a test at low temperature, SOI-STJ placed on the lowest stage.



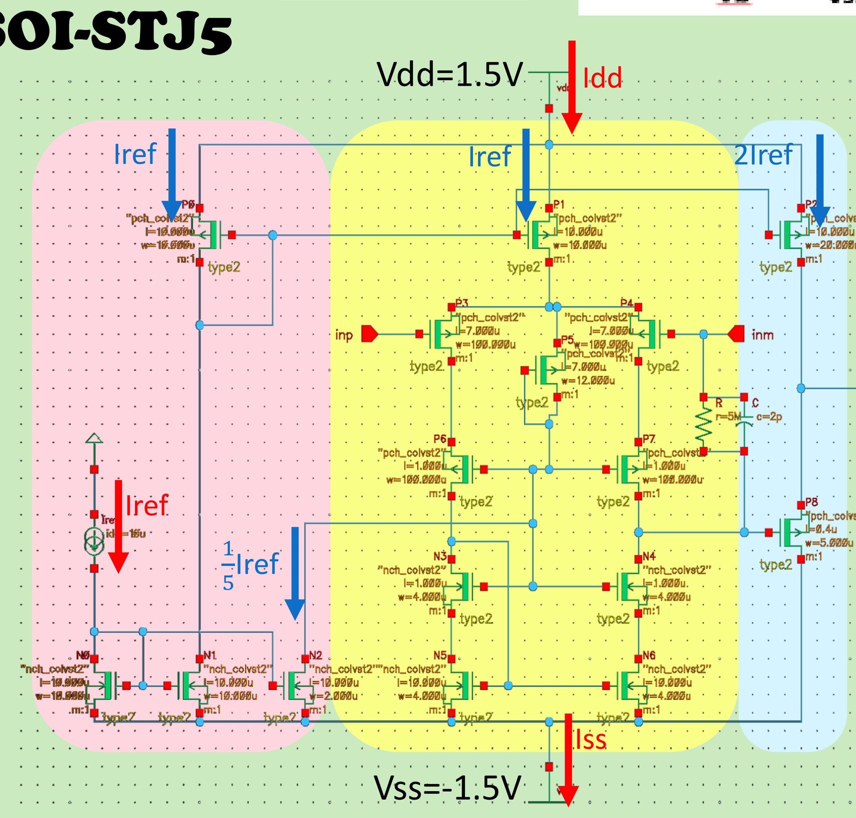
SOI-STJ4

- SOI-STJ4 is common source amplifier.
- SOI-STJ4 made a success to amplify the STJ signal for the first time! It has a gain around 64.





SOI-STJ5

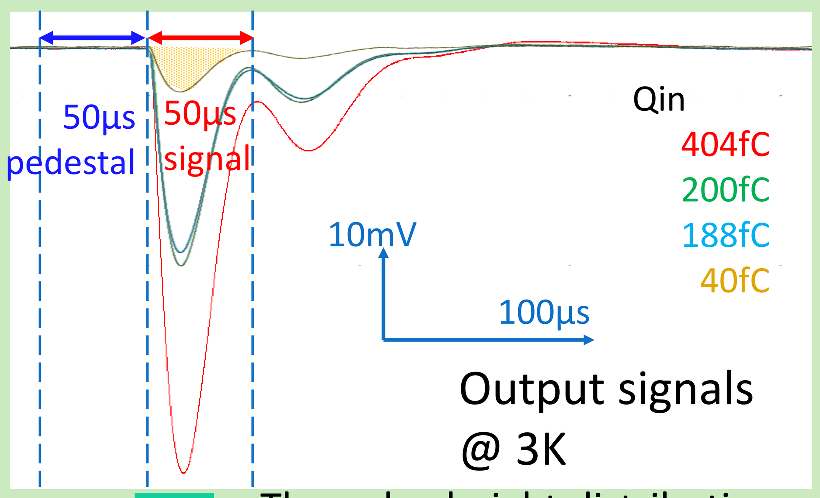


Buffering Stage
Source Follower Circuit
✓ Improvement of frequency band
Amplifying Stage
Op-Amp with Negative Feedback
✓ Lowering input impedance
Bias Circuit
Current Mirror Circuit
✓ Cope with array of detector
✓ Applying I_{ref}=10μA, We observe I_{dd}=40μA and I_{ss}=-50μA.

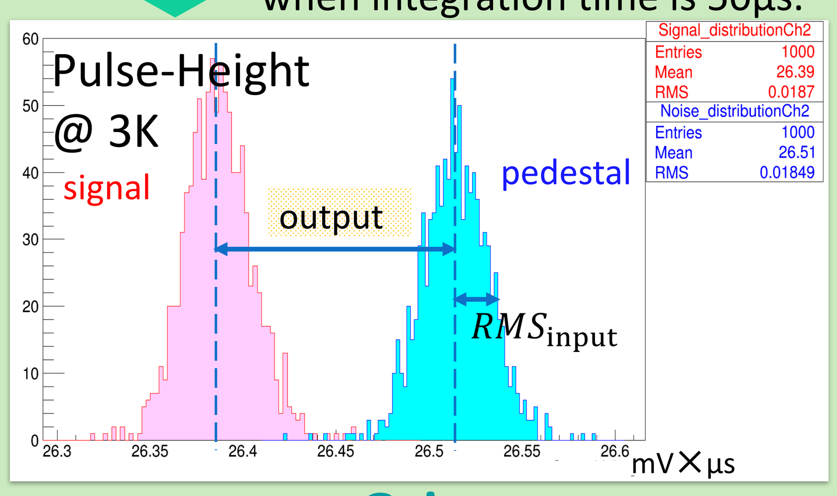
Failed Test of Charge Amplification

- The large current is coursed by drain avalanche when $|V_{gs}|<|V_{ds}|$ and $|V_{ds}|$>1V, since carriers have high mobility at low temperature. Simulating operation points at all MOSFETs in SOI-STJ5, I located MOSFETs working within drain avalanche-area in bias circuit.

Assessment of SOI-STJ5 without Bias Circuit

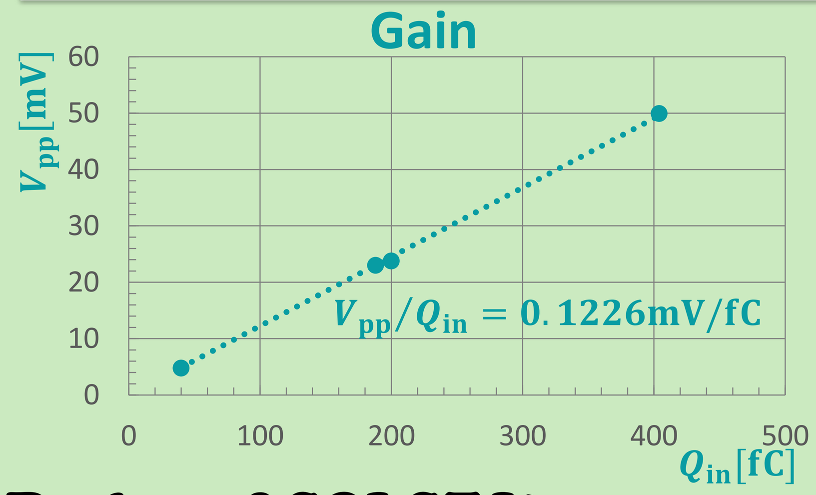


The pulse-height distribution when integration time is 50μs.

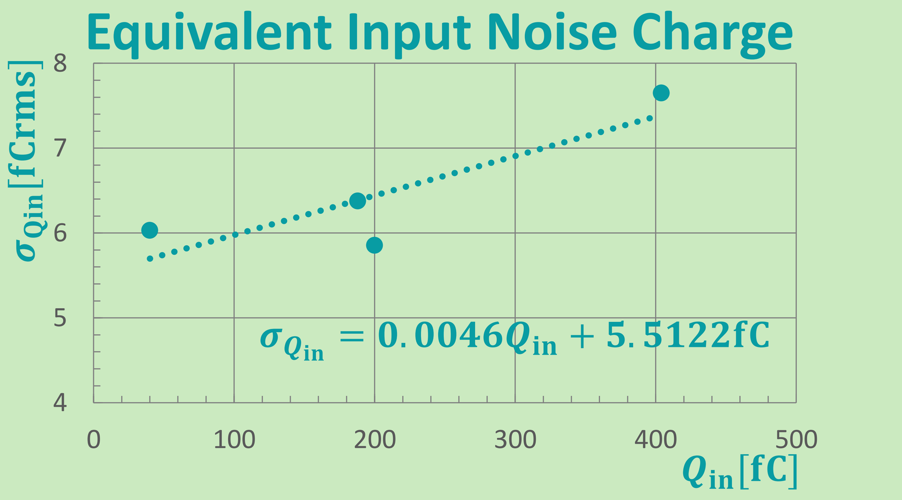


- Amplifying stage, buffering stage, the feedback resister and the feedback capacitor are bonded each other by Al wire.
- Applying I_{refa}=-10μA, I_{reft}=-2μA and I_{refb}=-20μA, We observe I_{dd}=60μA and I_{ss}=-28μA.
- The circuit works correctly at 3K much as measurement at room temperature.
  - ✓ Magnitude of output signal $V_{pp\sim}$ 46mV (Q_{in}=404fC)
  - ✓ Gain〜123mV/pC
  - ✓ Equivalent input noise charge σ_{Q0}〜5.5fC

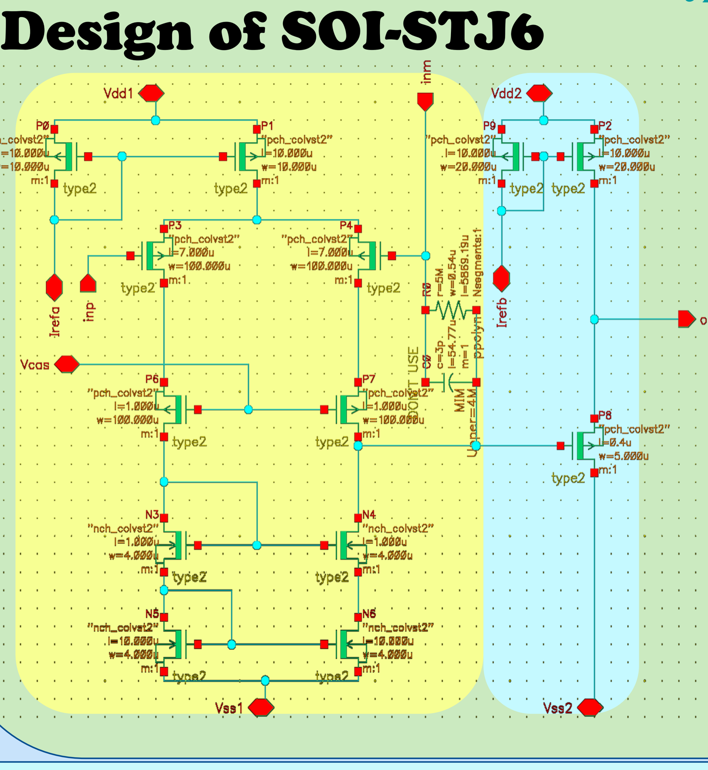
Gain



Equivalent Input Noise Charge



Design of SOI-STJ6



- Amplifier stage of SOI-STJ6 has a higher gain.
- 4 patterns for feedback capacitances
  - ✓ 3pF
  - ✓ 300fF
  - ✓ 60fF

Using 300fF or 60fF, we can detect a STJ signal for a visible single-photon.

- We designed two-steps amplifying SOI amplifier using SOI-STJ6 amplifier stage and SOI-STJ4 circuit. The two-steps SOI-STJ6 will obtain output signal magnitude about 30〜40mV at a STJ signal for a neutrino decay single-photon in λ=50μm.

4. Summary

- COBAND experiment is aiming to measure neutrino decay photons for a decision of neutrino masses.
- The cryogenic operational amplifier using FD-SOI MOSFET is being developed.

✓ SOI-STJ4 succeeded amplifying the STJ signal.
✓ SOI-STJ5 w/o bias circuit works as intend at low temperature.
✓ SOI-STJ5 w/o bias circuit has a gain around 123mv/pC.
✓ Equivalent input noise charge is about 5.5fC.
✓ SOI-STJ6 was designed to have higher gain.
✓ The two-steps SOI-STJ6 was designed to obtain 30〜40mV output signal at a STJ signal for a far-infrared single photon.