# R&D of quantum photo-sensor based on superconductor with cryo-SOI readout

INAUGURAL SYMPOSIUM FOR THE TOMONAGA CNETER FOR THE HISTORY OF THE UNIVERSE

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# Motivation

- **Neutrino's mass is not zero.**
  - Heavier neutrino can decay into lighter neutrino.
  - An energy of photon from neutrino decay is given

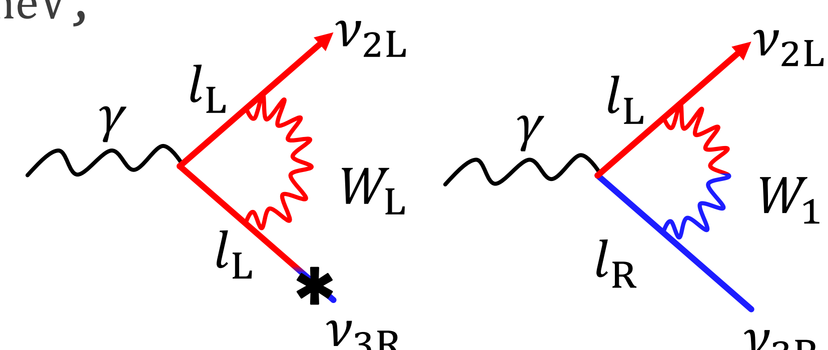
$$E_\gamma = \frac{|m_3^2 - m_2^2|}{2m_3}.$$

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

⇨ Can obtain neutrino mass to measure the energy.

  - Assuming $m_1 \ll m_2 < m_3$ and $m_3 = 50\ \mathrm{meV}$, the energy is expected
    $E_\gamma = 25\ \mathrm{meV}\ (\lambda = 50\mu\mathrm{m})$.

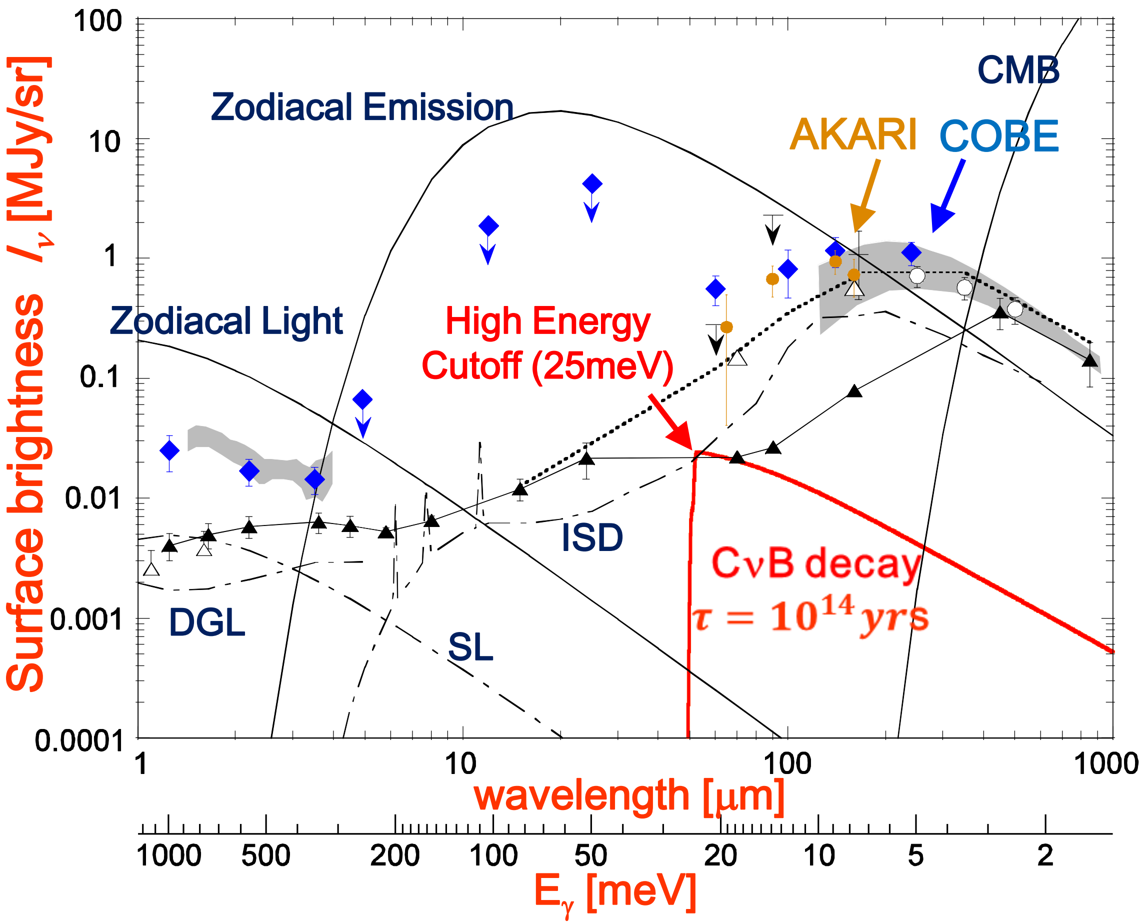
- **Neutrino's lifetime is very long.**
  - $\tau_{SM} \sim 10^{43}$ years
  - $\tau_{LRSM} \sim 10^{17}$ years




Standard model　　Left-Right symmetric model

⇨ Search for neutrino decay using Cosmic Background Neutrino (CvB, $\rho \sim 110\ /\mathrm{cm}^3$) as the neutrino source.

# Signal of CvB Decay and Backgrounds




- **Surface Brightness**
  - Zodiacal Emission
    $I_\nu \sim 8$ MJy/sr
  - Cosmic Infrared Background
    $I_\nu \sim 0.1 \sim 0.5$ MJy/sr
  - CvB Decay
    $\tau = 10^{14}$ years
    $I_\nu \sim 25$ kJy/sr $(\lambda = 50\ \mu\text{m})$

By measuring the energy spectrum continuously, we can see the CvB decay signal as a high energy cutoff.

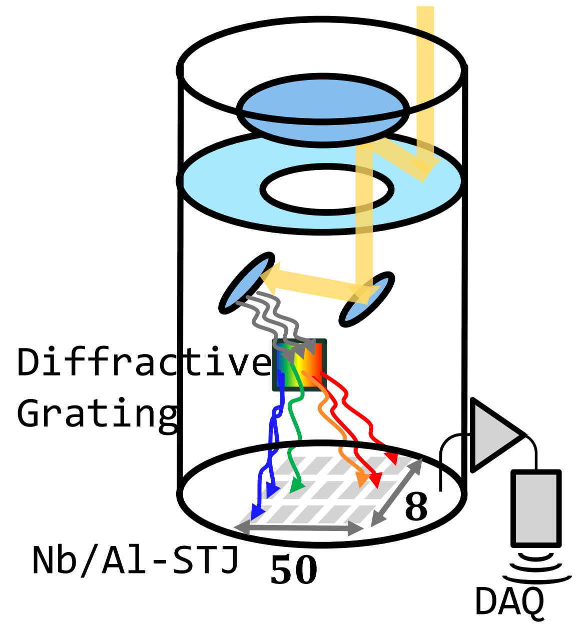
To identify the shape edge, we need detector which has better than 2% resolution for $E_\gamma = 25$ meV ($\lambda$=50 μm).

# COBAND Experiment
# COsmic BAckground Neutrino Decay search

## Rocket Experiment

- 200sec data acquisition at 200km height
- Using 50×8 array of Nb/Al-STJ pixels with diffractive grating covering $\lambda = 40\sim80\ \mu\text{m}$, we count photons for each wavelengths.

⇨ Improvement the lower limit of neutrino lifetime from O($10^{12}$) years to O($10^{14}$) years.



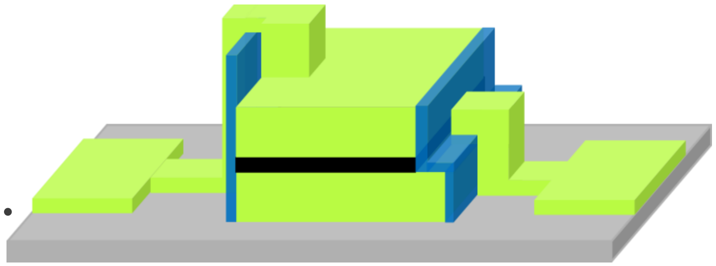

## Satellite Experiment

- 100days measurement at satellite
- STJ detector using Hafnium (Hf-STJ) achieves 2% energy resolution if fano factor $< 0.3$ for $E_\gamma = 25\ \text{meV}$.

⇨ Aiming at a sensitivity to neutrino lifetime for O($10^{17}$) years.

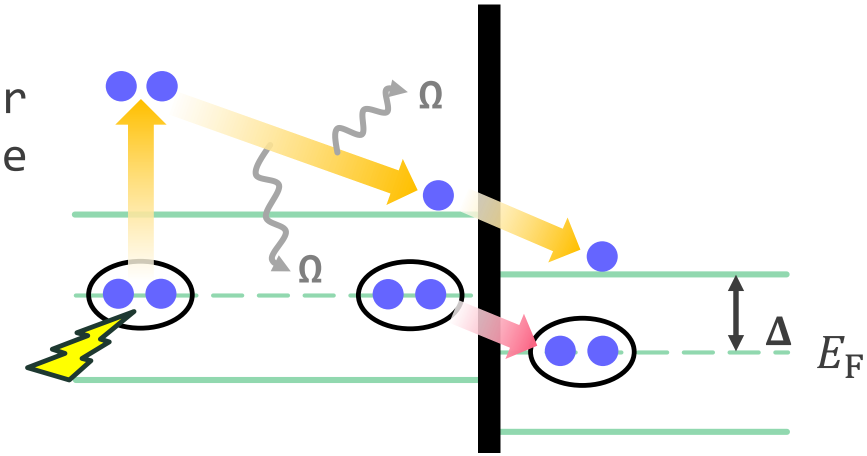
# STJ Detector
# Superconducting Tunnel Junction

## Structure



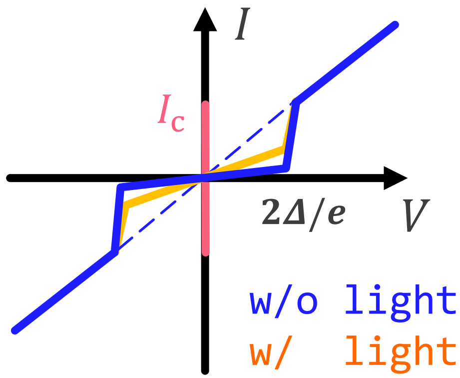
- STJ is detector consist of Superconductor/Insulator/Superconductor.

## Working Principle



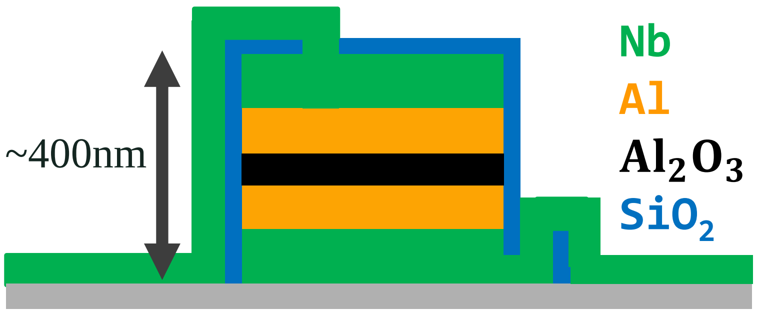

- An incident photon excites cooper pairs into quasi-particles in the superconductor.
- By applying a bias voltage, the quasi-particle tunnel through insulator.

## Characteristic of I-V Curve




- Josephson current can suppress by magnetic field.
- Leak current is constant below 1/10 of critical temperature.

# Development of Nb/Al-STJ




Size: 10μm✕10μm ~ 200μm✕200μm

| | Nb | Al | Hf |
|---|---|---|---|
| Δ[meV] | 1.550 | 0.172 | 0.021 |
| $T_c$[K] | 9.20 | 1.14 | 0.13 |

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

## Performance of our Nb/Al-STJ

- The signal width <10μs
- The number of quasi-particles generated by 25meV single photon is

$$N_e = G_{\mathrm{Al}} \frac{E_\gamma}{1.7\Delta} \sim 250.$$

- The resolution is

$$\delta N_e / N_e \sim 15.5\%$$

$E_\gamma$: energy of incident photon
$G_{\mathrm{Al}}$: trapping gain ~10
Δ: band gap ~0.57meV
(Nb:100nm, Al:70nm)

Back tunneling effect to enhance quasi-particles density

## Requirement in Rocket Experiment

- Leak current < 100pA

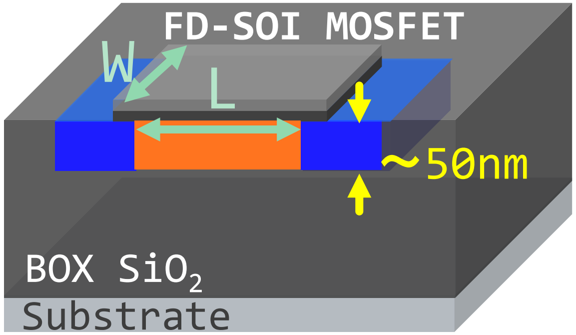
Nb/Al-STJs can count far infrared single photons and achieved the requirement for leak current.

# SOI-STJ
# R&D of Cryogenic Amplifier

Nb/Al-STJs have not detected far infrared single photon yet. It is affected by the large noise from the refrigerator’s readout line about 5m.

Amplify the STJ signal by cryogenic amplifier placed near STJ.

- **Requirement for the cryogenic amplifier**
  - Operation at cryogenic temperature (<3K)
  - Fast response speed (width of signal <10μs)
  - Low power consumption

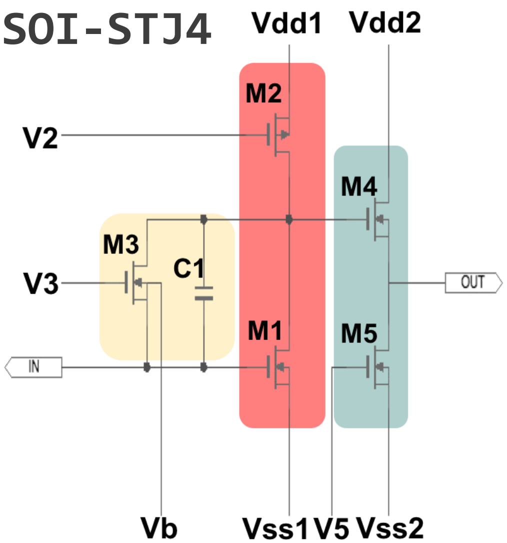



- **FD-SOI(Fully Depleted-Silicon On Insulator) MOSFET**
  - FD-SOI MOSFET has the nano-channel layer.
  - Low power consumption
  - Suppress charge-up of the body

※JAXA/ISAS confirmed working of MOSFET under FD-SOI process at 4K.
T. Wada et al., J. Low. Temp. Phys. 167, (2012) 602

⇨ Using FD-SOI MOSFET, we have developed the cryogenic amplifier (SOI-STJ).

# Amplifying STJ Signal by SOI-STJ4




**Amplification**

Common source amplifying circuit

Replaced the resistance by M2

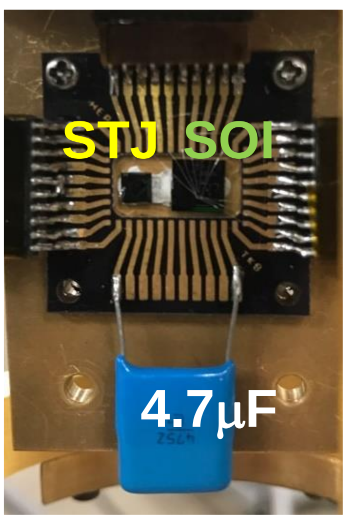
**Feedback**

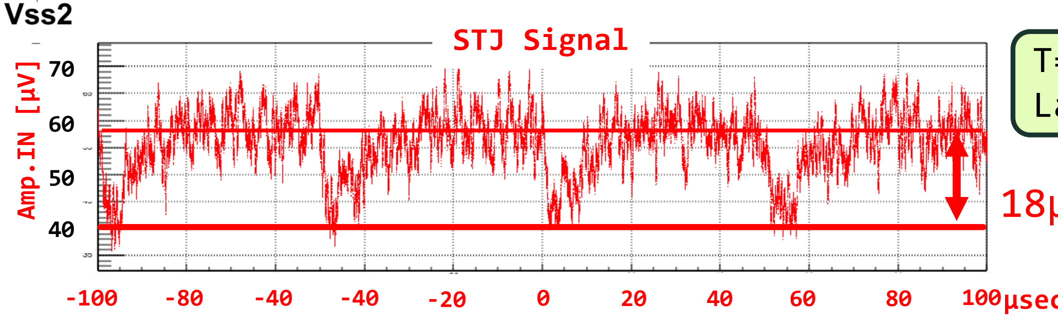
Given a suitable input offset voltage by M3.

**Buffer**

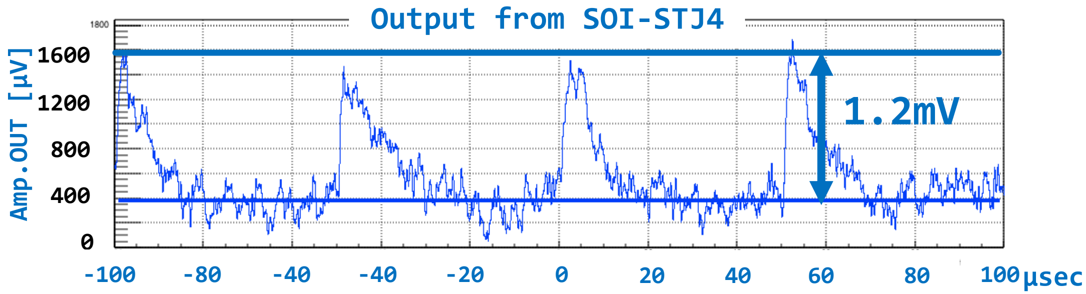
Source follower circuit

Reduce the output impedance by M4 and M5.




T=350mK
Laser: λ=465nm,f=20kHz



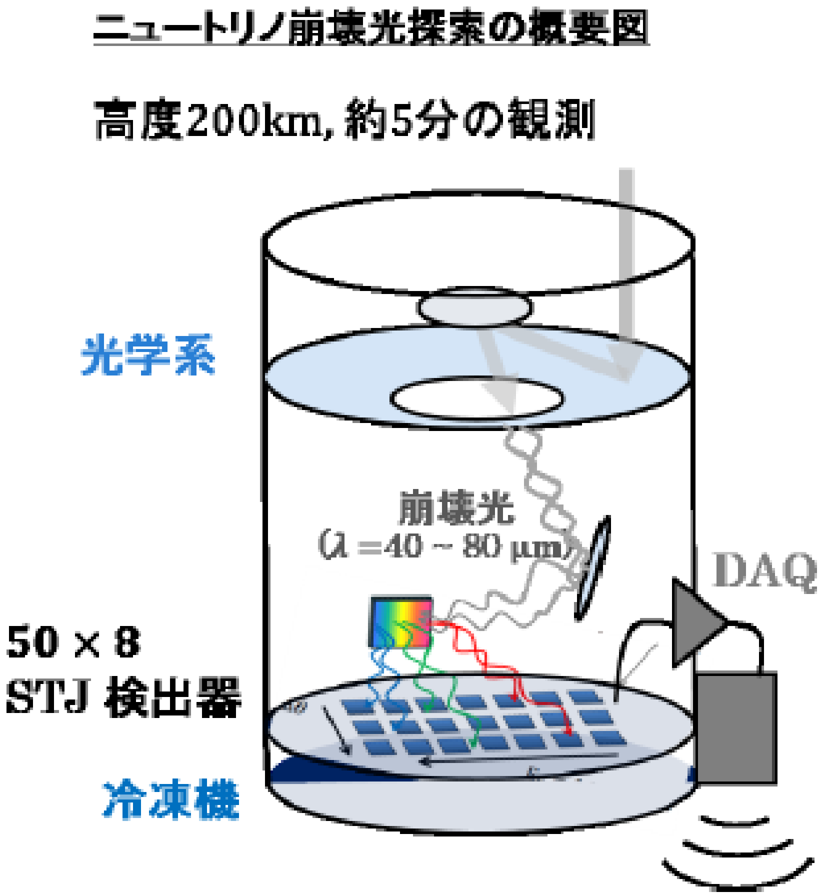

SOI-STJ4 succeeded in amplifying the STJ signal!

# Summery

- COBAND Experiment aims to measure neutrino masses.
- We have developed the STJ photo detector and cryogenic amplifier using FD-SOI-MOSFET (SOI-STJ) for rocket experiment.
- Nb/Al-STJs have achieved the requirement in rocket experiment.
- SOI-STJ4 succeed in amplifying the STJ signal for visible laser.

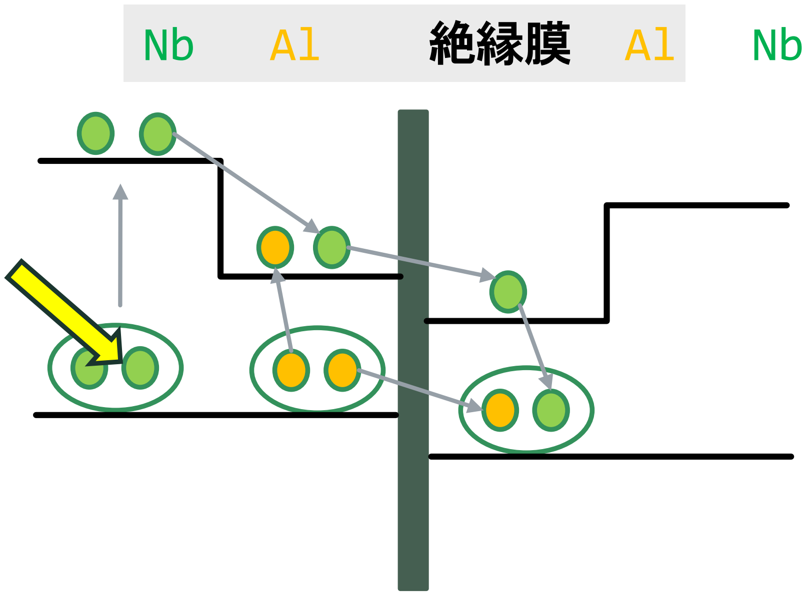
# Backup

# ロケット実験




- データ収集
  - 上空200km
  - 収集時間200sec
- 50×8の検出器を使用
  - 検出器としてNb/Al-STJを使用
  - 遠赤外光が入射したかを検出
- 3Heソープション減圧冷凍機を使用
  - 到達温度：0.4K
- ニュートリノの寿命の下限値を修正
  - $\tau > 10^{14}$years
  - 有意度$5\sigma$

# バックトンネリング効果

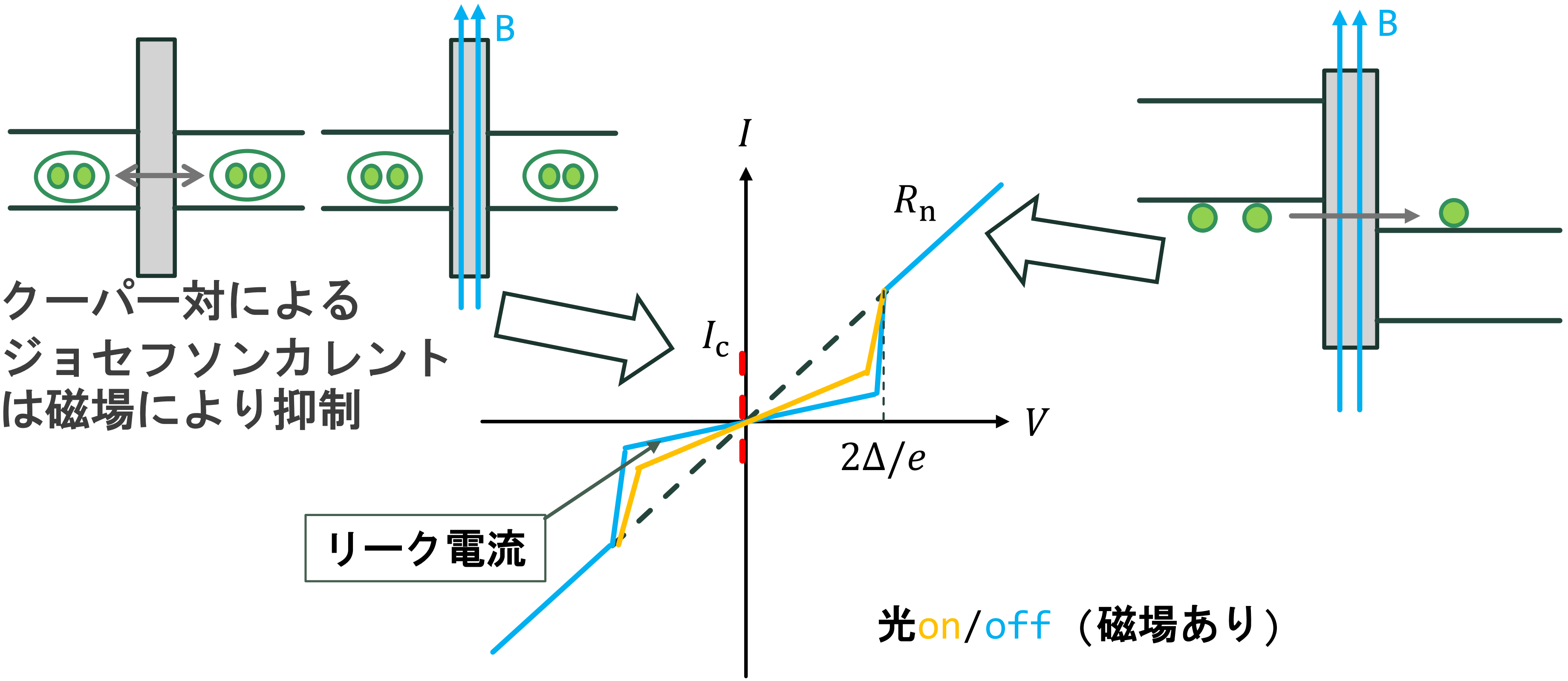



- バックトンネリングの仕組み
  - ✓ Nb層に光が入射し、クーパー対が励起して準粒子を生成
  - ✓ 生成された準粒子内あるものはそのままトンネル
  - ✓ トンネルしなかった準粒子はAl層での準粒子の存在確率を高める
  - ✓ トンネルした準粒子がAl層の**クーパー対**
    **の片割れと**クーパー対を作る
  - ✓ その際に余った電子が準粒子としてAl層で励起

- Nb/Al-STJではG~10

# STJの電流-電圧カーブ

- 光応答を見る際は$|V| < 2\Delta/e$の範囲の変化が見られるような電流値に固定する
  - ✓ リーク電流がノイズとなる



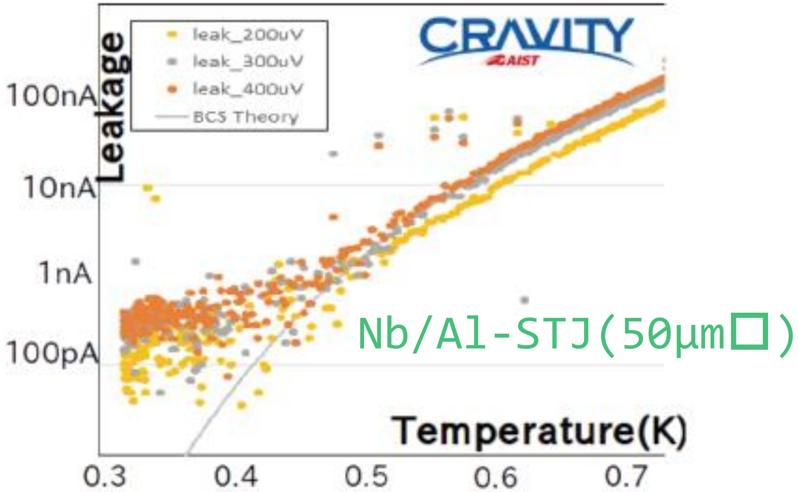
# リーク電流への要求

- Nb/Al-STJで25meVの1光子を測定する
  - ✓ 生成電荷数：$N_{sig} = G_{\mathrm{Al}} * \frac{E_\gamma}{1.7\Delta} = 10 \times \frac{25\mathrm{meV}}{1.7\times0.6\mathrm{meV}} \sim 250$
  - ✓ ノイズによる電荷数：$N_{leak} = \frac{i_{leak}\times\tau}{e}$
  - ✓ $N_{sig}$の揺らぎ：$\delta N_{sig} = G_{\mathrm{Al}}\sqrt{F * \frac{E_\gamma}{1.7\Delta}}$
    Fano因子：$F\sim0.2$
  - ✓ $N_{leak}$の揺らぎ：$\delta N_{leak} = \sqrt{N_{leak}}$
  - ✓ STJの応答速度：$\tau\sim1\mu s$
- 信号が300Hzで入ってくると考え
  リークによるノイズを1/10,検出効率97.5%と要求
  - ✓ $4\sqrt{N_{leak}} = N_{sig} - 2\sqrt{\left(\sqrt{N_{leak}}\right)^2 + \left(\delta N_{sig}\right)^2}$

➡ $i_{leak}\sim250\mathrm{pA}$

**現在、20μm角のNb/Al-STJで$i_{leak}\sim100\mathrm{pA}$を達成！**

**リーク電流の温度依存性　産総研 藤井氏による測定**




M.Ukibe et al., Jpn. J.Appl. Phys. 51, 010115(2012)
M.Ohkubo et al., IEEE Trans. Appl. Super, 24, 2400208(2014)

| Nb/Al-STJ size | Leak current @300mK |
|---|---|
| 50μm×50μm | 224±29pA |
| 20μm×20μm | 39±13pA |
| 10μm×10μm | 14±7pA |

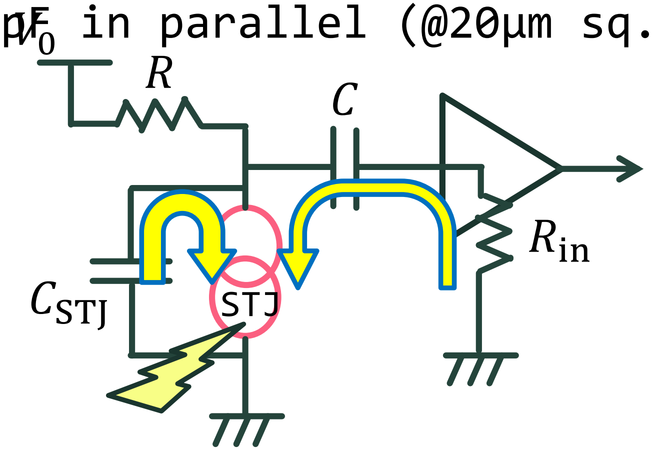
# Comparison between new and old SOI amplifiers

Circuit

## SOI-STJ4

- Common source circuit
- Input impedance $R_{\text{in}} \sim 20\text{k}\Omega$

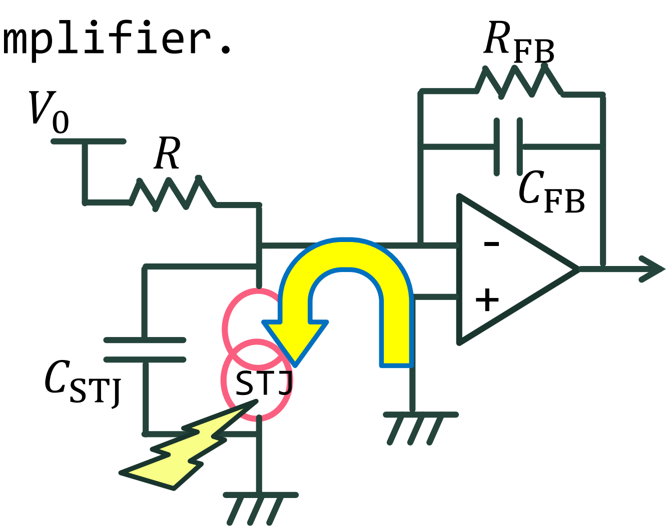
The signal charges transferred to SOI amplifier is ~1/6 of the total since the STJ has capacitance of 40pF in parallel (@20μm sq.).




## SOI-STJ5

- Charge integrating operational amplifier with negative feedback
- Low input impedance caused by negative feedback (ideally, 0Ω)

Almost all signal charges are transferred to the SOI amplifier.

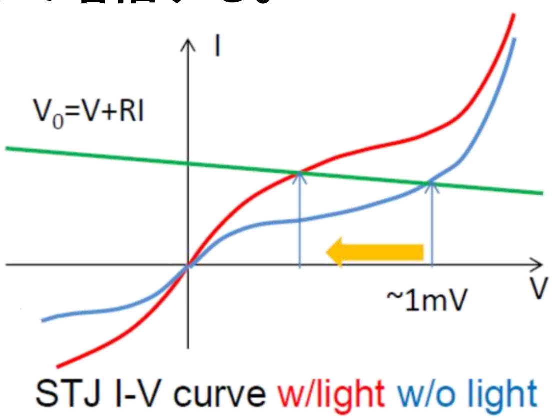


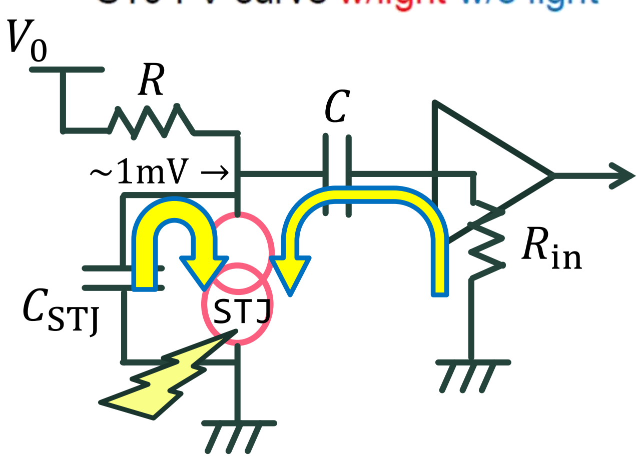
# 帰還付き差動増幅回路による
# 極低温電荷積分型増幅器の開発

## SOI-STJ4

### ■ 定電流モード

SOI増幅器はSTJ信号の電圧変化を読んで増幅する。



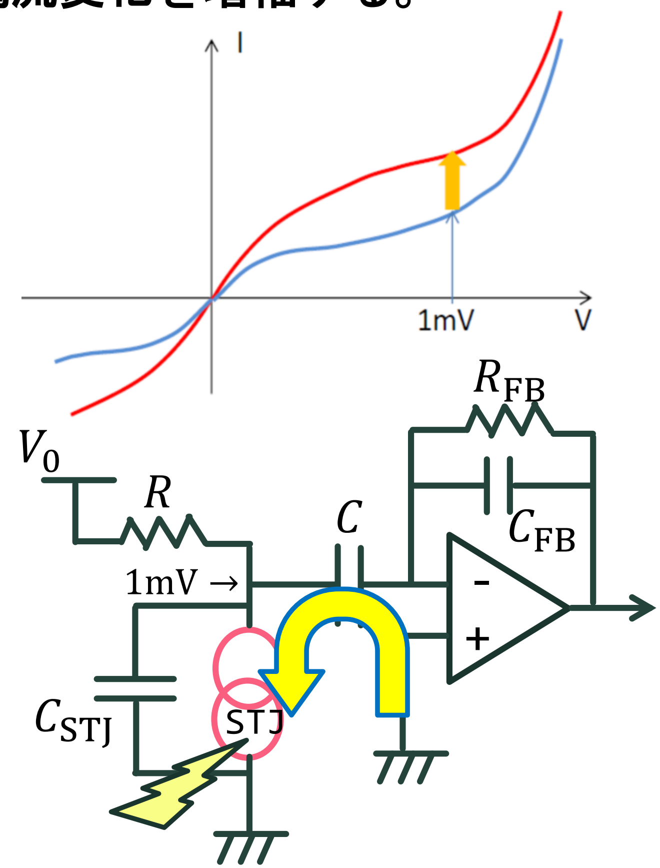




## SOI-STJ5

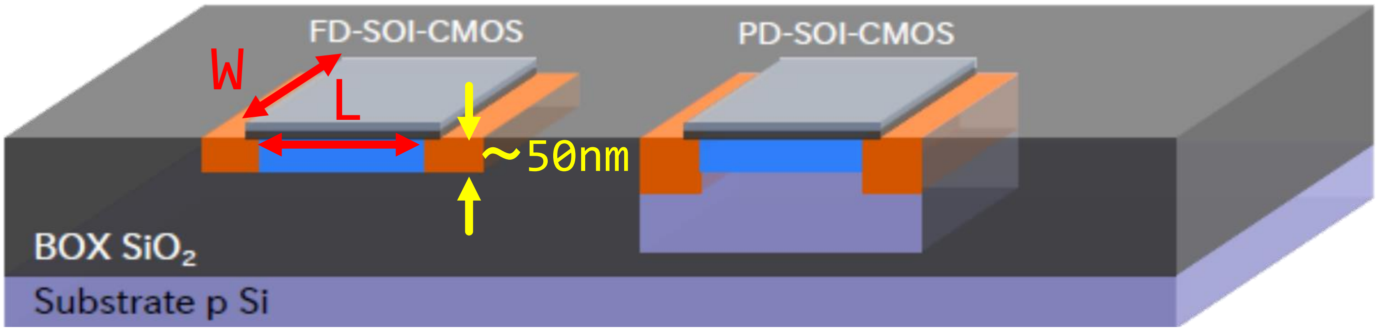
**変更点**

### ■ 定電圧モード

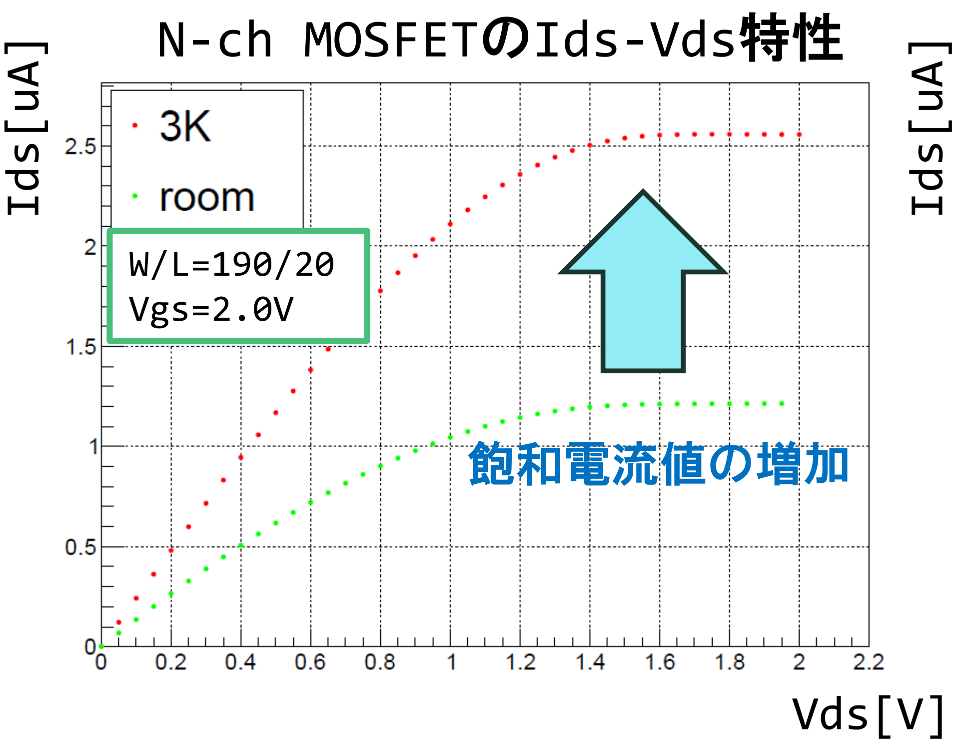
SOI増幅器はSTJ信号の電荷変換された電流変化を増幅する。

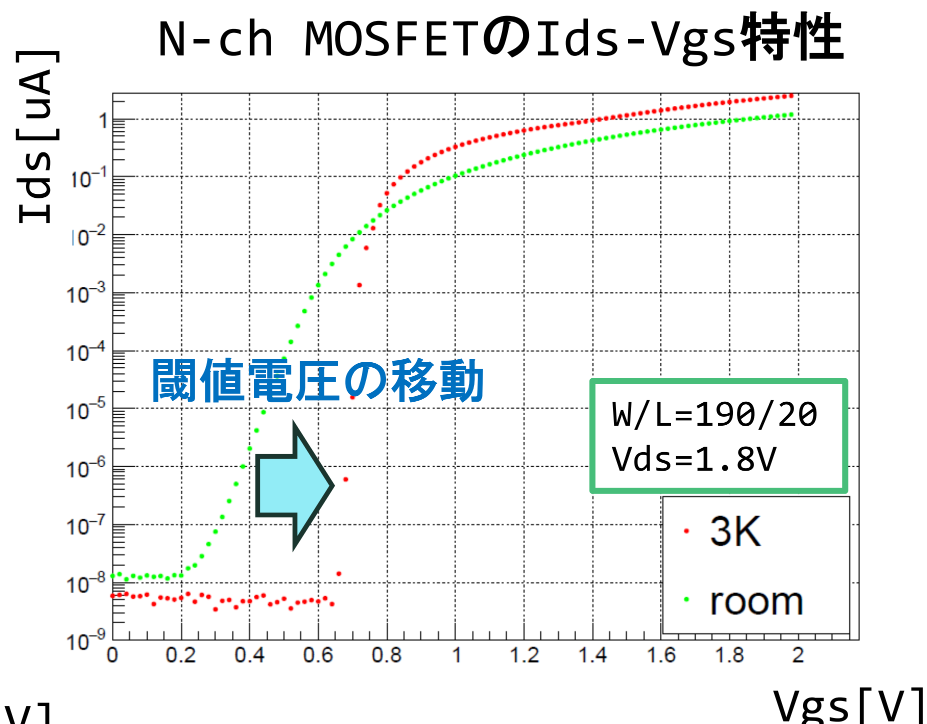


# 極低温におけるFD-SOI-MOSFET




- FD-SOI
  Fully Depleted - Silicon On Insulator
  - 省消費電力
  - 浮遊帯効果の抑制



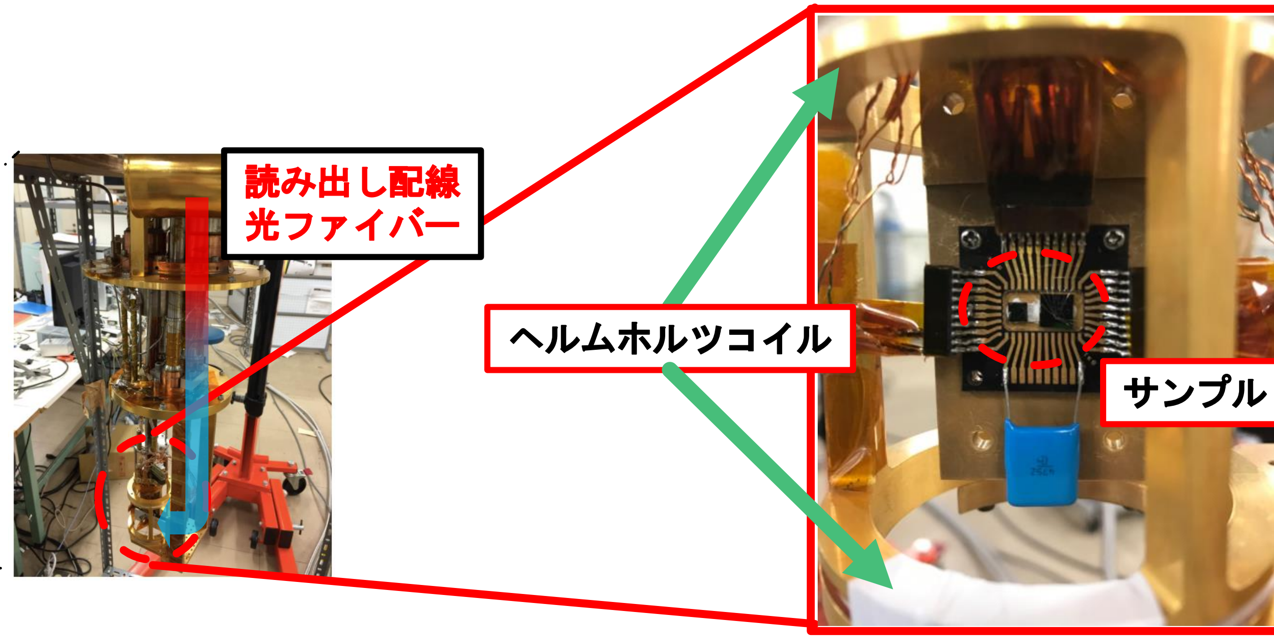




極低温において特性は変化するが、適切な動作点を使用すれば問題はない。

# 測定環境

He3 Sorption冷凍機
(Oxford Instrument製)

中を見ると




$He^3$減圧冷凍機　冷却能力一覧

| ステージ | 最低到達温度[K] | 冷却能力 |
|---|---|---|
| 60Kステージ | 60 | 25W @65K |
| 3Kステージ | 2.8 | 0.7W @4.2K |
| 最低温ステージ | 0.3 | 100μW @350mK |

各ステージには
熱輻射を防ぐために
シールドがある