新学術領域研究「ニュートリノフロンティアの融合と進化 2016」

R&D Status of Nb/Al-STJ with SOI cryogenic preamplifier

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COBAND COLLABORATION

Contents

COsmic BAckground Neutrino Decay Search

● Neutrino Decay

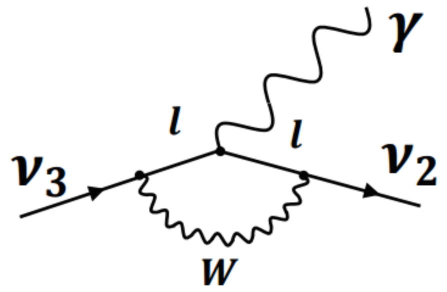
We can determine the neutrino mass itself by measuring the neutrino decay photon energy and using the difference between the mass-squares(Neutrino Oscillation EXP.)

measure precisely！

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

Neutrino oscillation

Neutrino Decay



- Neutrino has a long lifetime (T > O(10^{12}) years : COBE+AKARI measurement)
  - ✧ We need a large number of neutrino
    →we use the Cosmic Background Neutrino!!

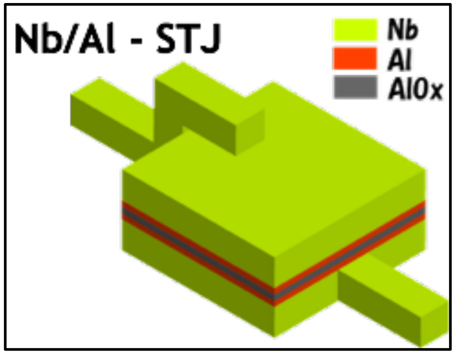
The expected E_γ : 25meV (Frequency : 6 THz)

The photon detector has to detect THz Photon!!

We use the superconducting tunnel junction

Superconducting Tunnel Junction

Superconducting Tunnel Junction : STJ



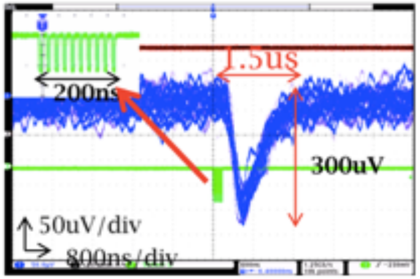
Working principle of STJ

1. An incident photon breaks cooper pairs into quasi-particles in the superconductor
2. The quasi-particles tunnel through insulators , and we can detect the current.

Response Speed

The signal width of STJ : 1.5us

(In case that 10 pulse lights inject into STJ in 200ns)



The number of quasi-particle which is generated

$$N_q = G_{\mathrm{al}} \cdot \frac{E_0}{1.7 \times \Delta}$$

Gal : trapping gain
E_0 : Energy of photon
Δ : energy gap

The number of quasi-particles generated by 25meV single photon (Al layer : 70nm)

$$N_q = 10 \cdot \frac{25meV}{1.7 \times 0.6meV} = 245e$$

Development of Nb/Al - STJ

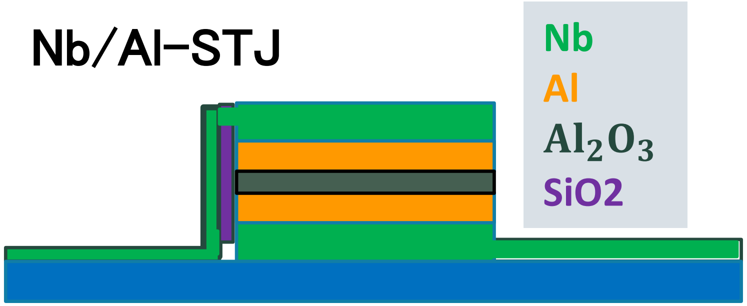
Our Nb/Al – STJ is fabricated at AIST CRAVITY facility.

[structure]

Nb / Al / AlOx / Al / Nb

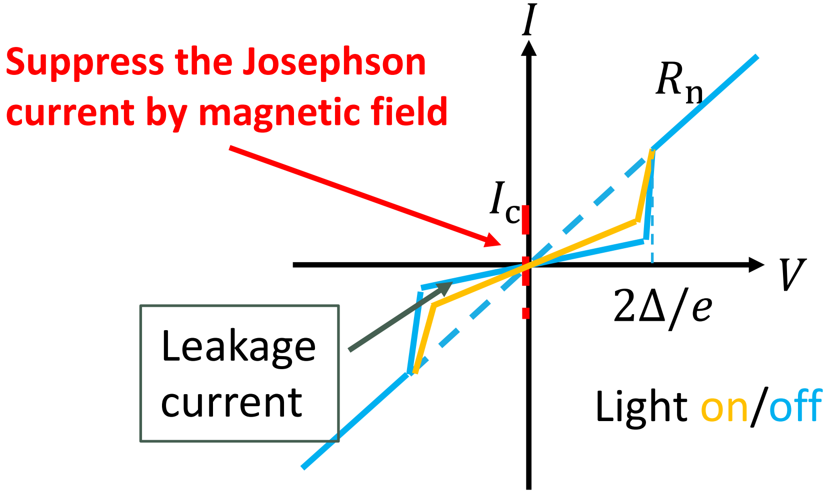
-> 100nm / 70um / 1nm / 70nm / 200nm

Nb/Al−STJ

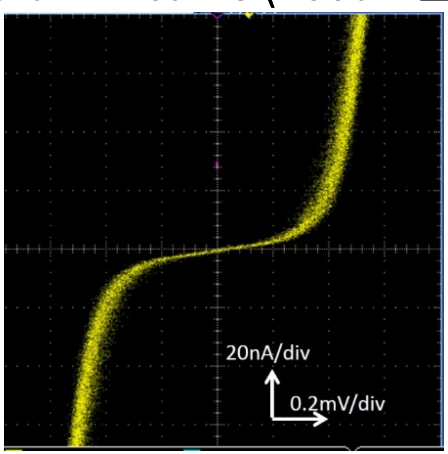


	Nb	Al
T_c[K]	9.23	1.12
Δ[meV]	1.550	0.172

[General IV characteristic of STJ]



STJ IV – curve (100um□)



Size	I_{leak} @0.4mV
100um□	2 nA
50um□	300 pA
20um□	100pA

The requirement for cold pre-amplifier

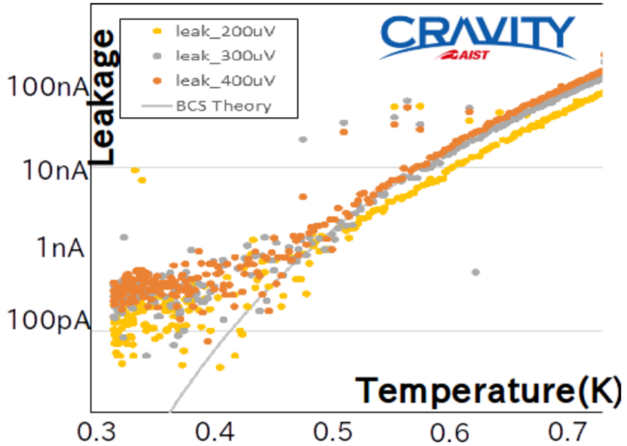
STJ Detector

- ✓ Required I_{Leak} : < 100pA
- ➢ Current Status : 100pA (20μm☐ Nb/Al-STJ)
- ➢ Achieving the demand of the I_{Leak}

But , we have not been able to observe a far-infrared single photon , because of the large readout electronics noise.

➢ **We install the cold pre-amplifier near STJ!!**

Leakage Current of Nb/Al – STJ(50um☐)
Temperature dependence



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

The requirement for cold pre-amplifier

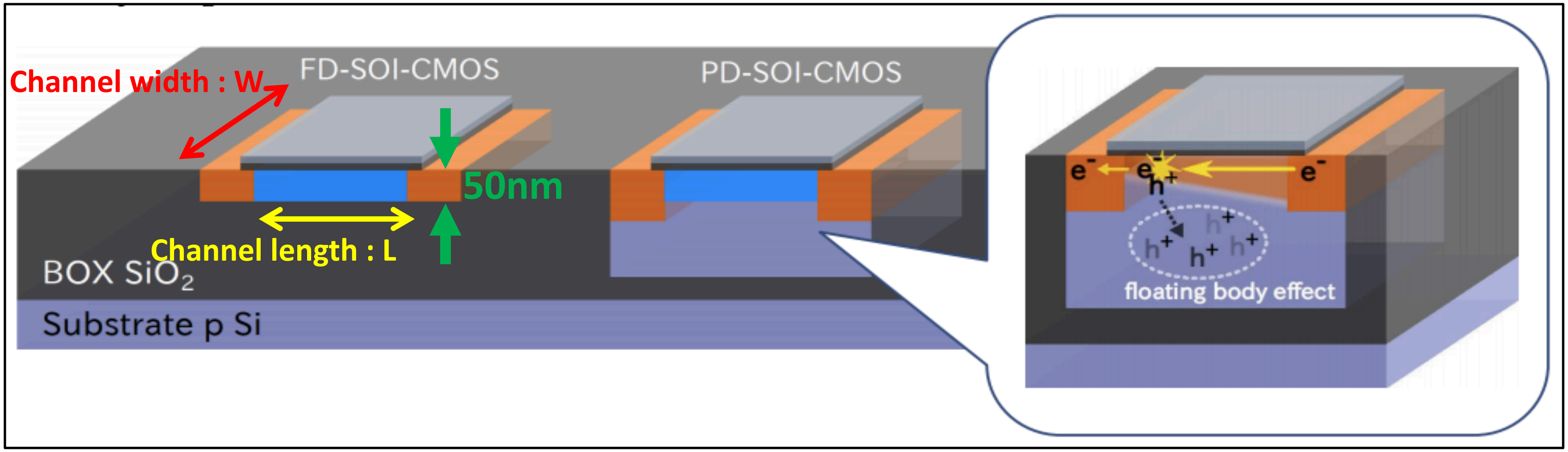
- ✓ Can be operated at the cryogenic temperature (< 3K)
- ✓ Amplification gain should be large enough up to 1MHz
- ✓ Power consumption should be lower than cooling power of the refrigerator (※cooling power of our refrigerator: **100μW** @300mK , **0.25W** @4.2K)

SOI-MOSFET

FD-SOI : **F**ully **D**epleted – **S**ilicon **O**n **I**nsulator

- ➢ FD-SOI MOS-FET is a transistor that is processed on SiO_2 insulator
- ☐ Very thin channel layer
  - ☐ Suppress charge-up of the body due to high-mobility carrier at low temperature
- ✓ Actually ,this transistor is working at 4K!!

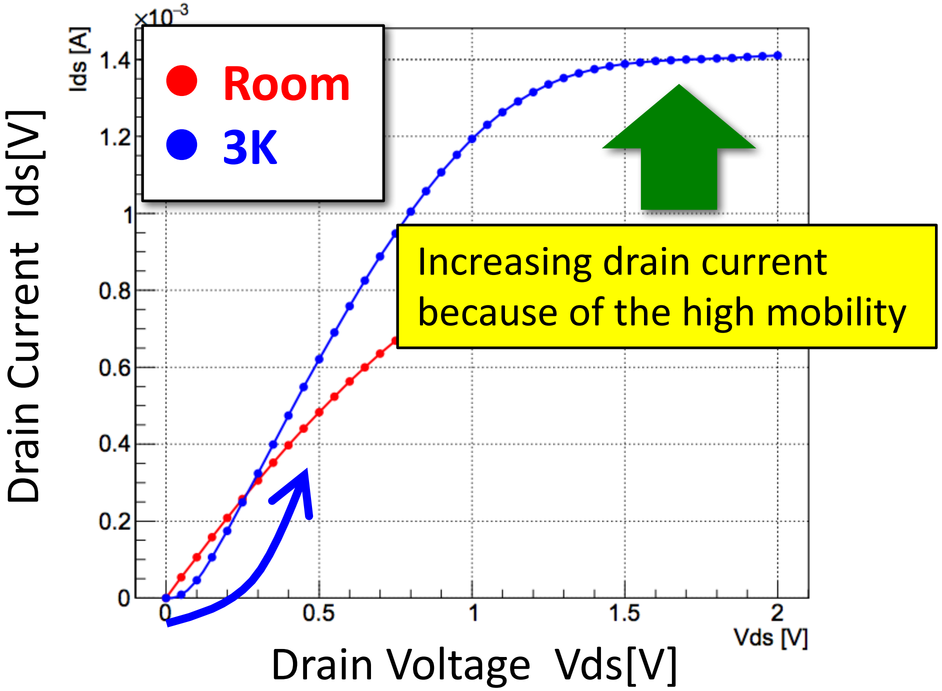
(reference : JAXA/ISAS **AIPC 1185,286-289(2009)**)



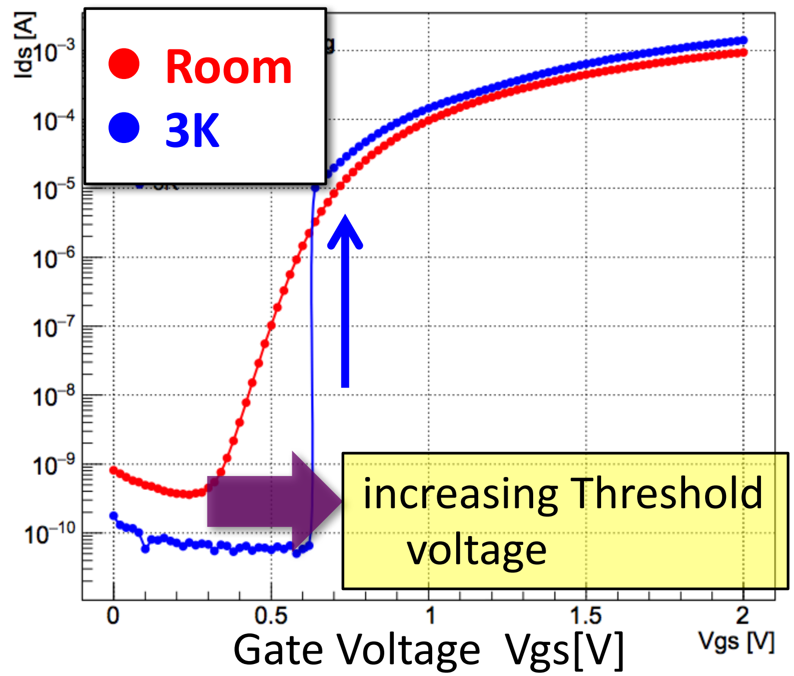
I-V characteristic of SOI-FET @3K

ex.) N channel : W/L = 10μm / 1.0μm

I_{drain} vs $V_{drain\text{-}source}$ Curve ($V_{gate\text{-}source}$=2V)



I_{drain} vs $V_{gate\text{-}source}$ Curve ($V_{drain\text{-}source}$=1.8V)



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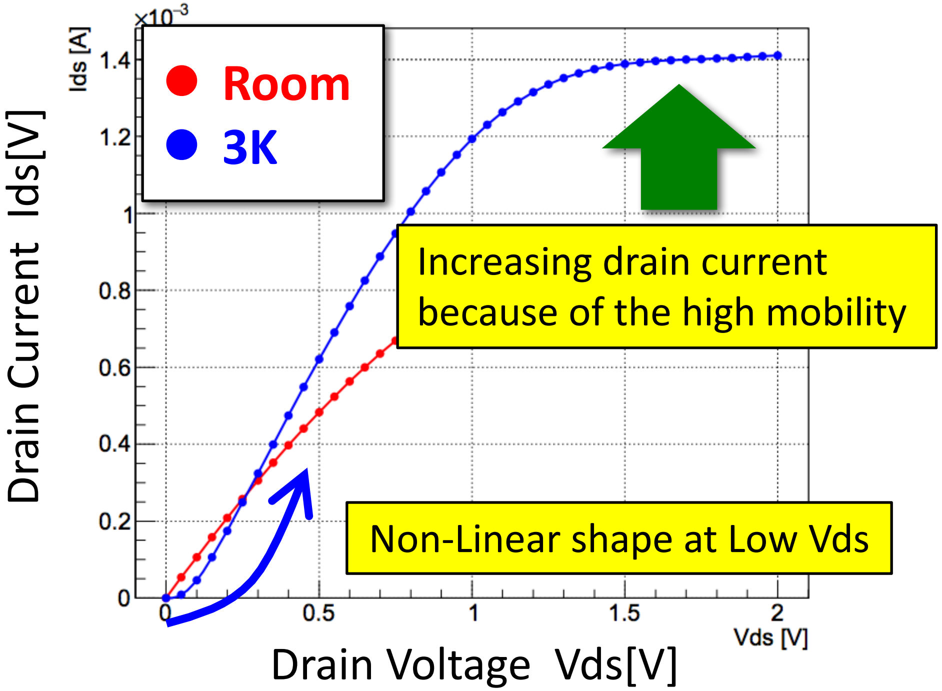
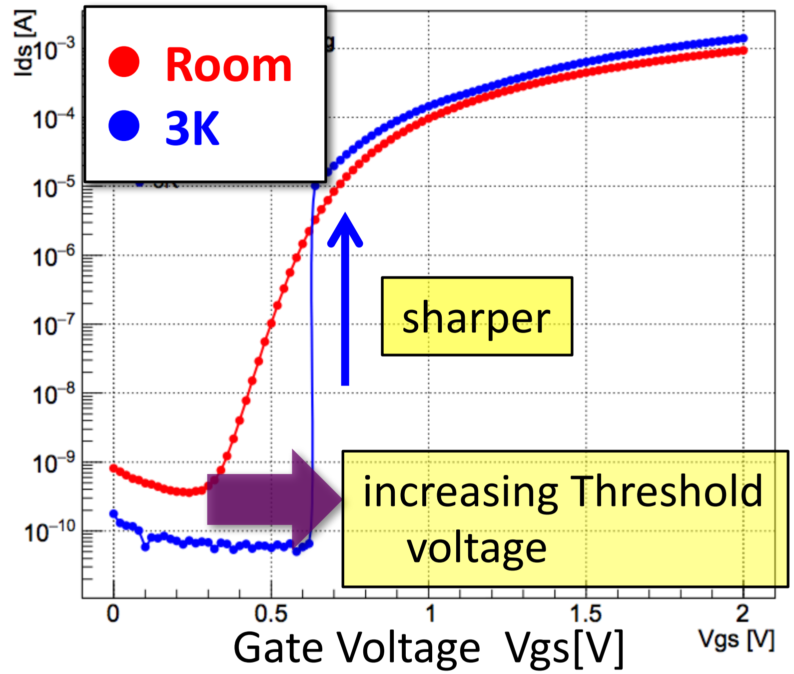
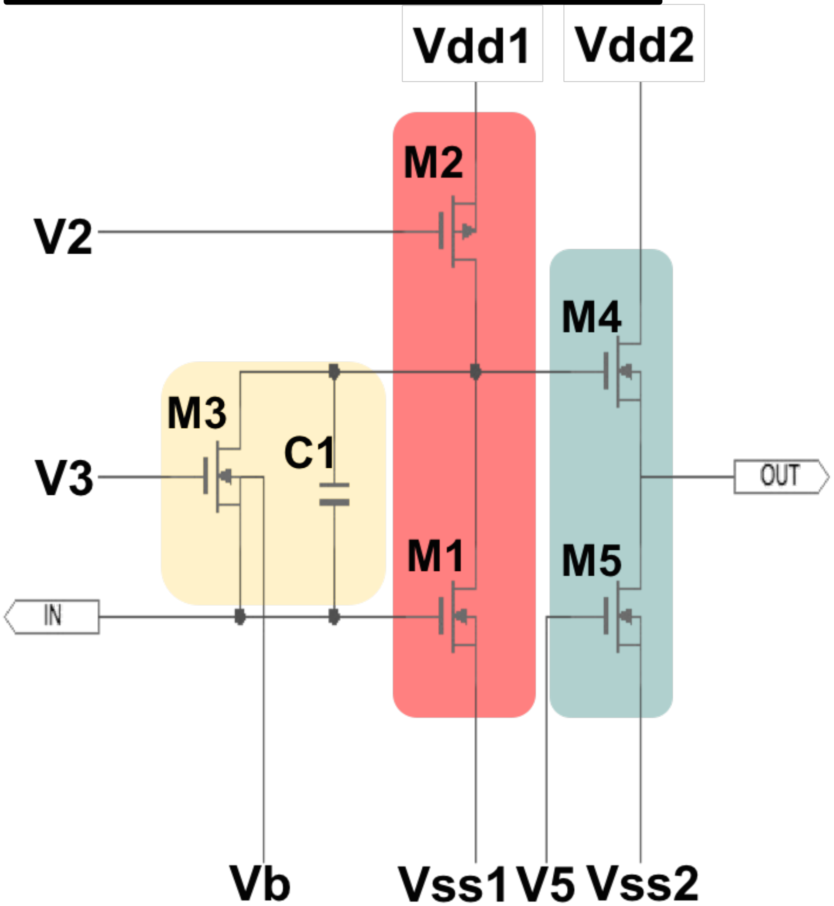


I_{drain} vs $V_{gate\text{-}source}$ Curve ($V_{drain\text{-}source}$=1.8V)



The design of cold preamplifier

SOI - STJ4 (the 4th trial Unit)

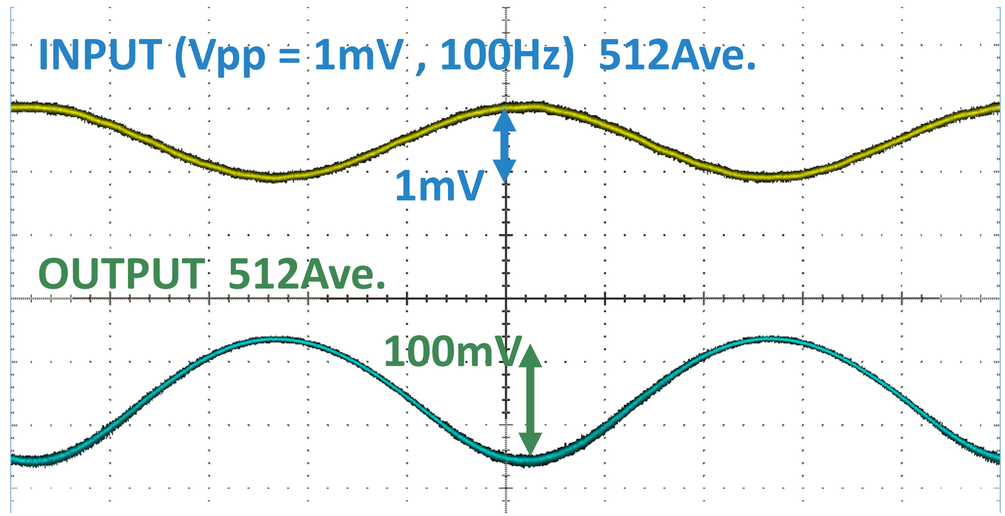


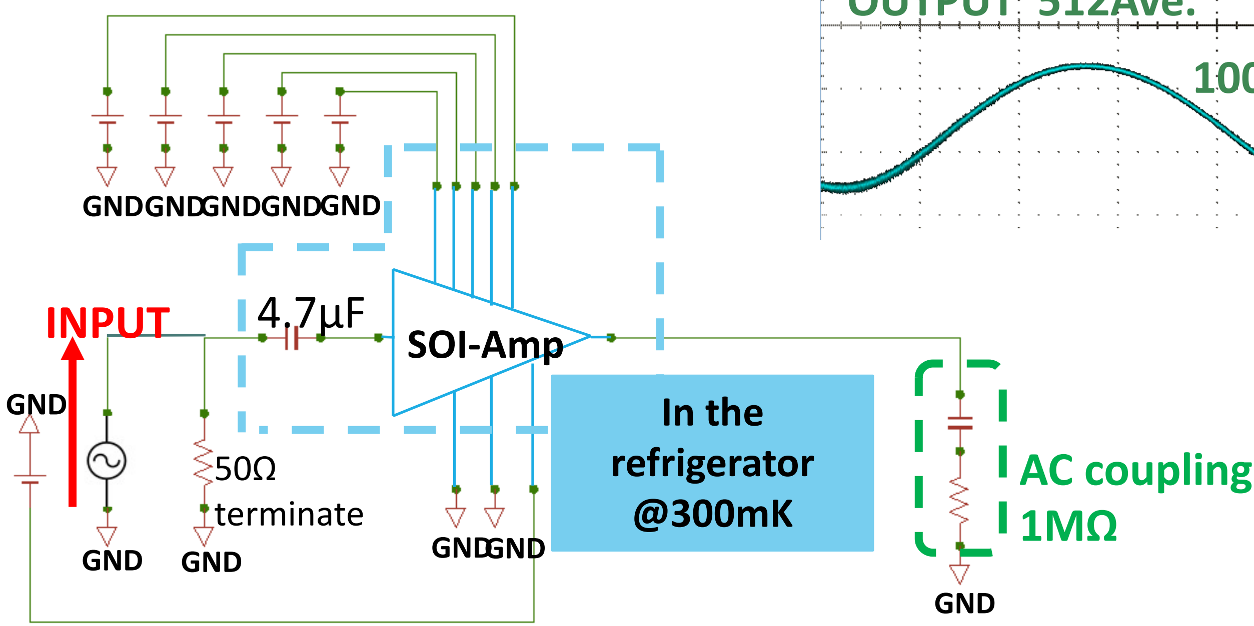
- **Common Source Amplifier**
  - Using MOS-FETs instead of resistance
- **Feedback Circuit**
  - Self bias voltage
- **Source Follower Circuit**
  - Output impedance is decreased

	Type	W [μm]	L [μm]
M1	Nch-CLst2	40	1
M2	Pch-CLst2	1	10
M3	Nch-CLst2	1.6	10
M4	Nch-CLst2	70	1
M5	Nch-CLst2	60	1
C2	MIM cap.	100 fF	

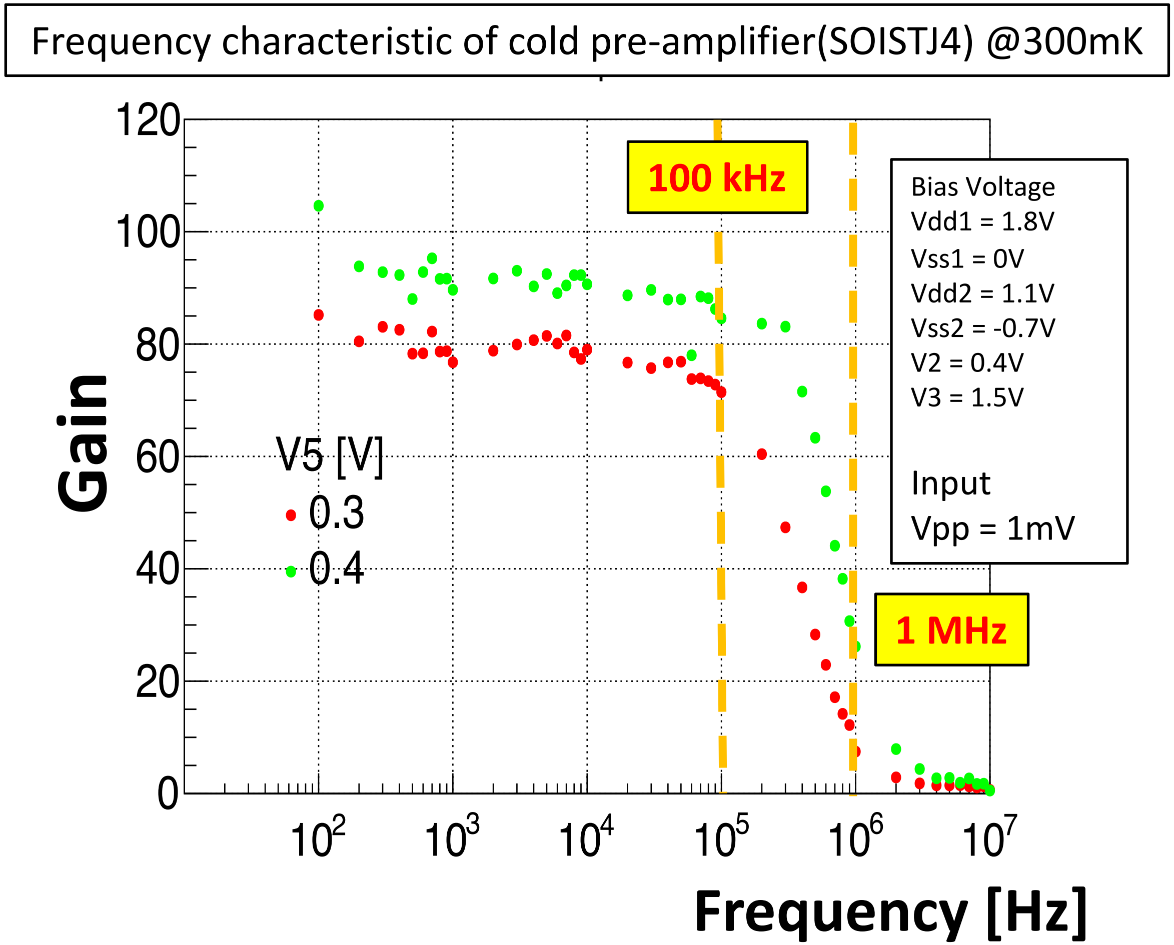
Test of amplifying sin-wave using SOI-Amp.

- INPUT : sin-wave
- Fit the bias voltage of SOI-Amp.
- Measured INPUT Frequency vs Gain characteristics!!





Frequency characteristics



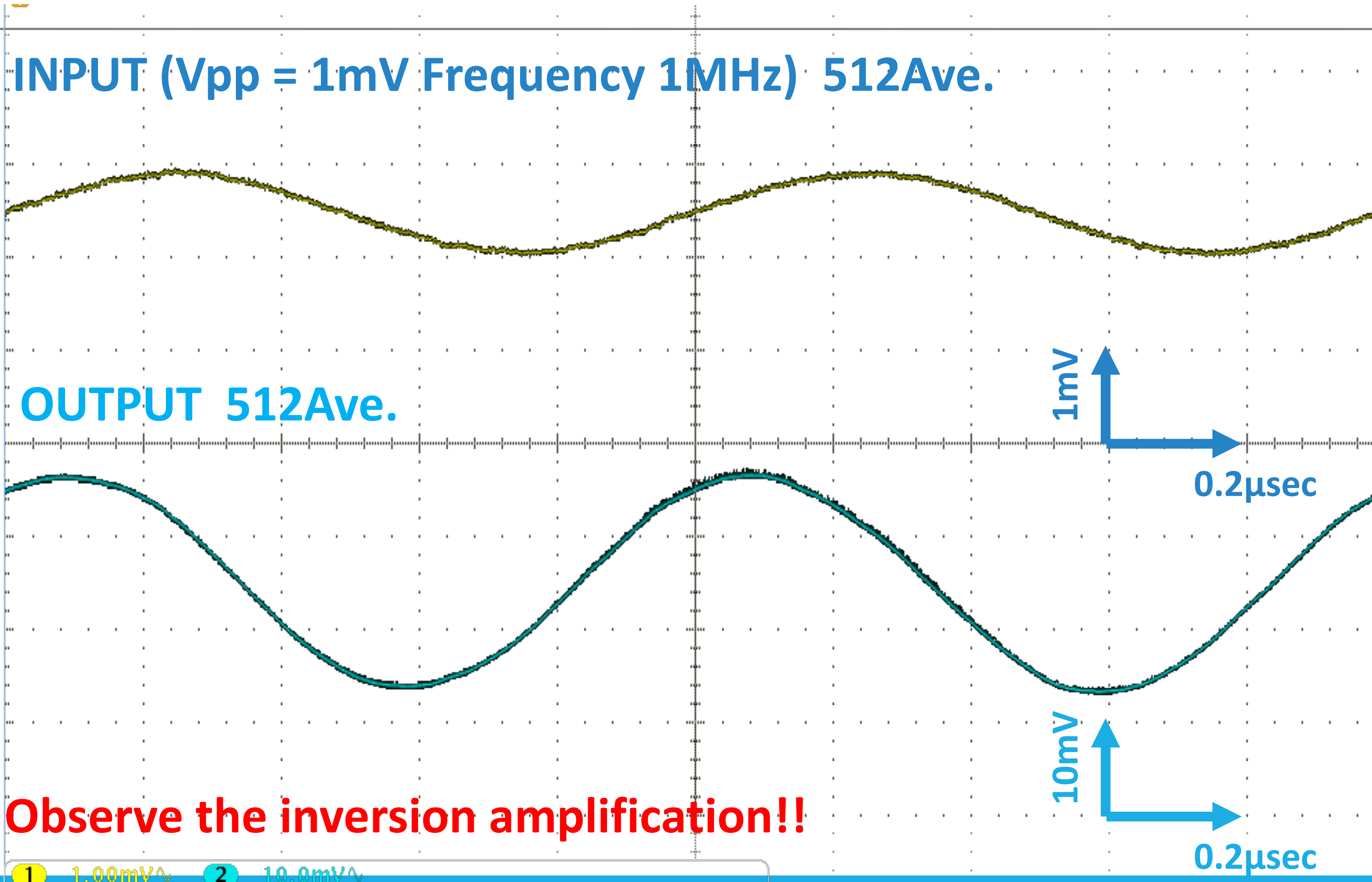
- **Adjust V3(Feedback) to earn amplifying gain**
  tuning V2 exactly not to saturate OUTPUT signal

- Then, scan V5
  and investigate the frequency characteristics.

- **Input 1MHz**
  Load capacitance : 0.5nF
  ---->> Gain ~ 20

- **Power Consumption : 230 uW**
  - **Larger than cooling power @300mK**

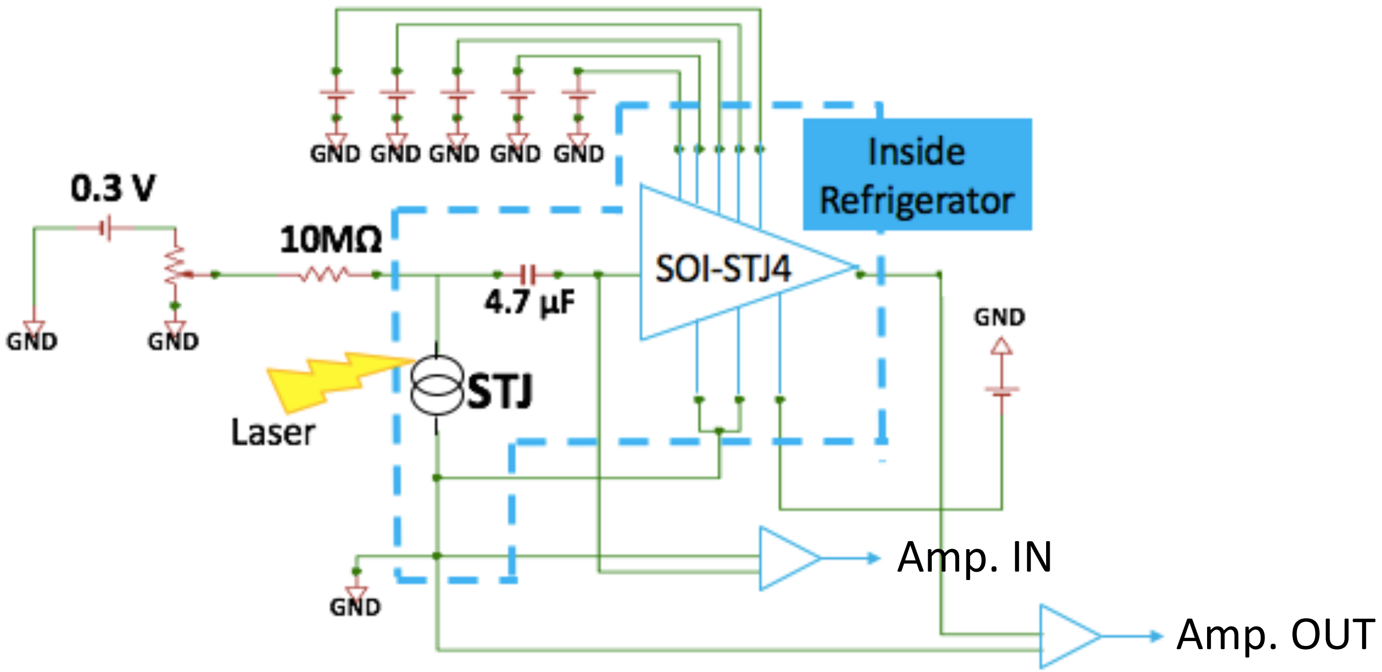
INPUT 1MHz



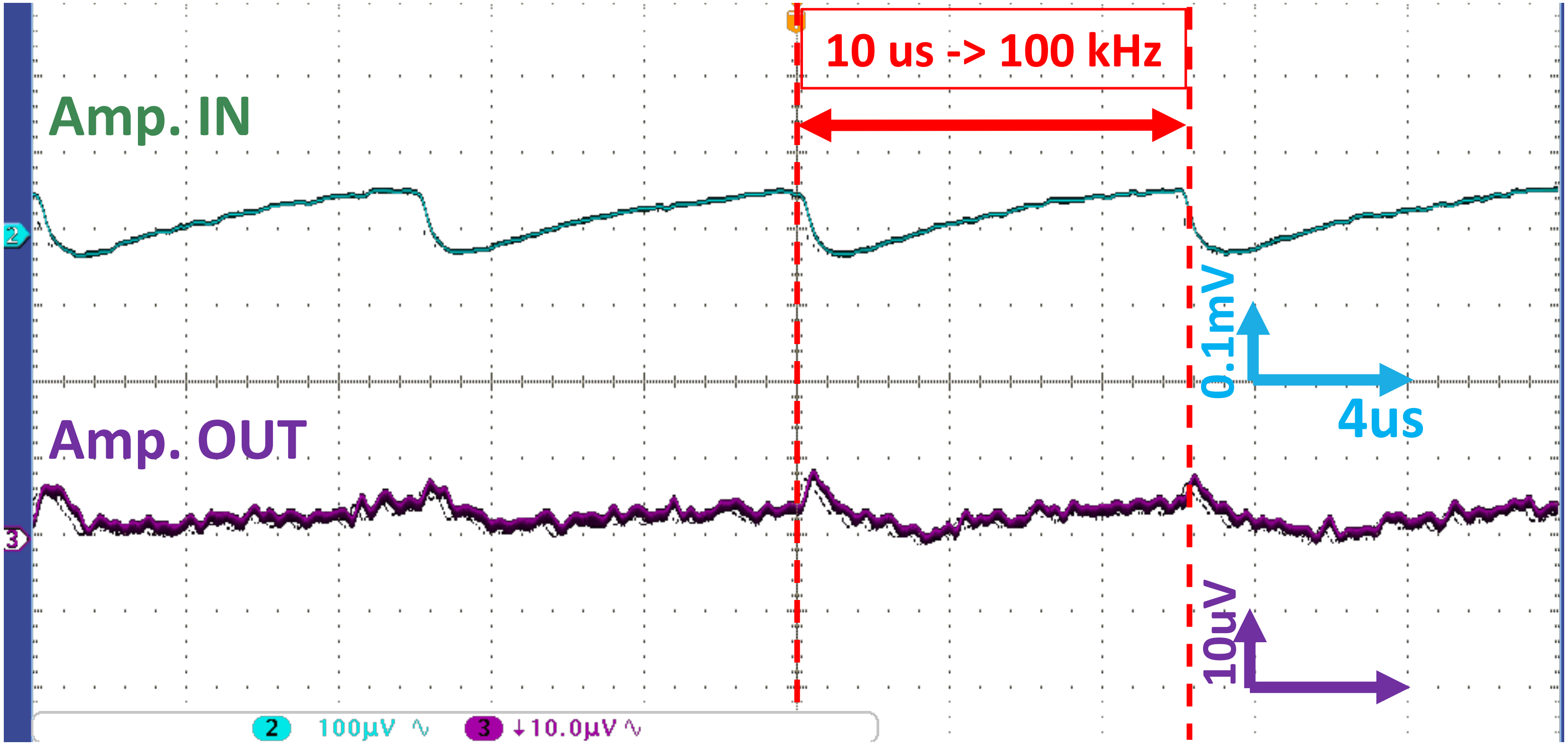
Observe the inversion amplification!!

Test of STJ signal amplification with the cold SOI-preamplifier

- Inject laser pulse into STJ and try to amplify STJ signals with cold amplifier
- I try to investigate
  1. whether STJ signal can be transferred into SOI-Amp.
  2. whether the transferred signal can be amplified by SOI-Amp.



Laser response @300mK



- I confirmed that STJ signals was transferred into SOI-Amp.
- But, INPUT signals were not amplified･･･
  - I found that SOI-Buffer did not work correctly･･･

Summary

- To search for neutrino decay, we are researching & developing
  1. Superconducting Tunnel Junction (STJ)
  2. SOI-STJ (that is a cold pre-amplifier which can be operated @300mK)

- We measured the frequency characteristic of SOI-Amplifier @300mK
  - Gain : 20~30 ----> INPUT :: 1MHz sin-wave Load Cap. :: 0.5nF
  - Gain : ~100 ----> INPUT :: <= 100kHz sin-wave

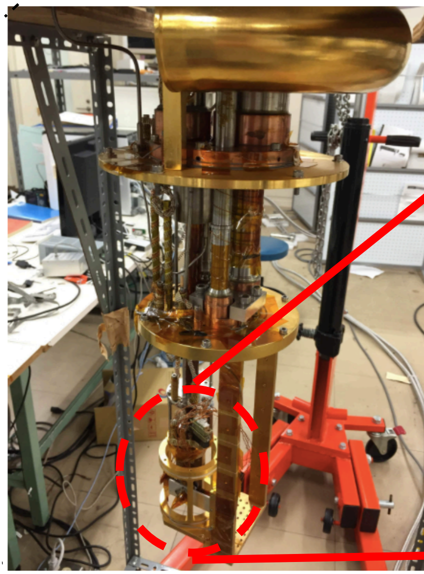
- We are trying to amplify the STJ signal to visible laser light.
  - I confirmed that STJ signals can be transferred into SOI-Amplifier.
  - But, SOI-STJ did not work correctly because of SOI-Buffer.
  - The test of the STJ signal amplification with the cold amplifier is underway

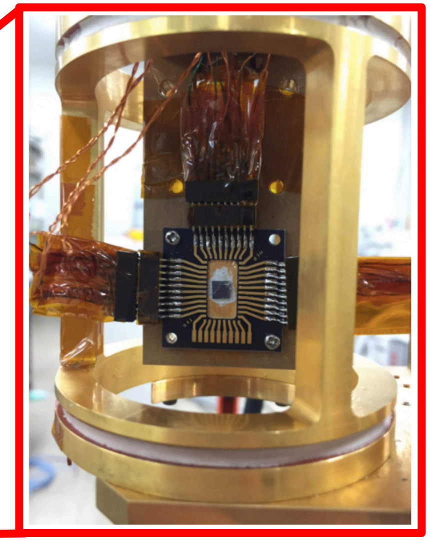
BACKUP

冷凍機のスペック

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	100uW @350mK

各ステージには
熱輻射を防ぐために
シールドがある

キャリア移動度

3Kでのキャリア移動度は常温のと比べて約2倍ほど大きくなると言われている。
本測定で移動度がどれだけ大きくなっているか検証する

線形領域・飽和領域でのドレイン電流の式は以下のようになる

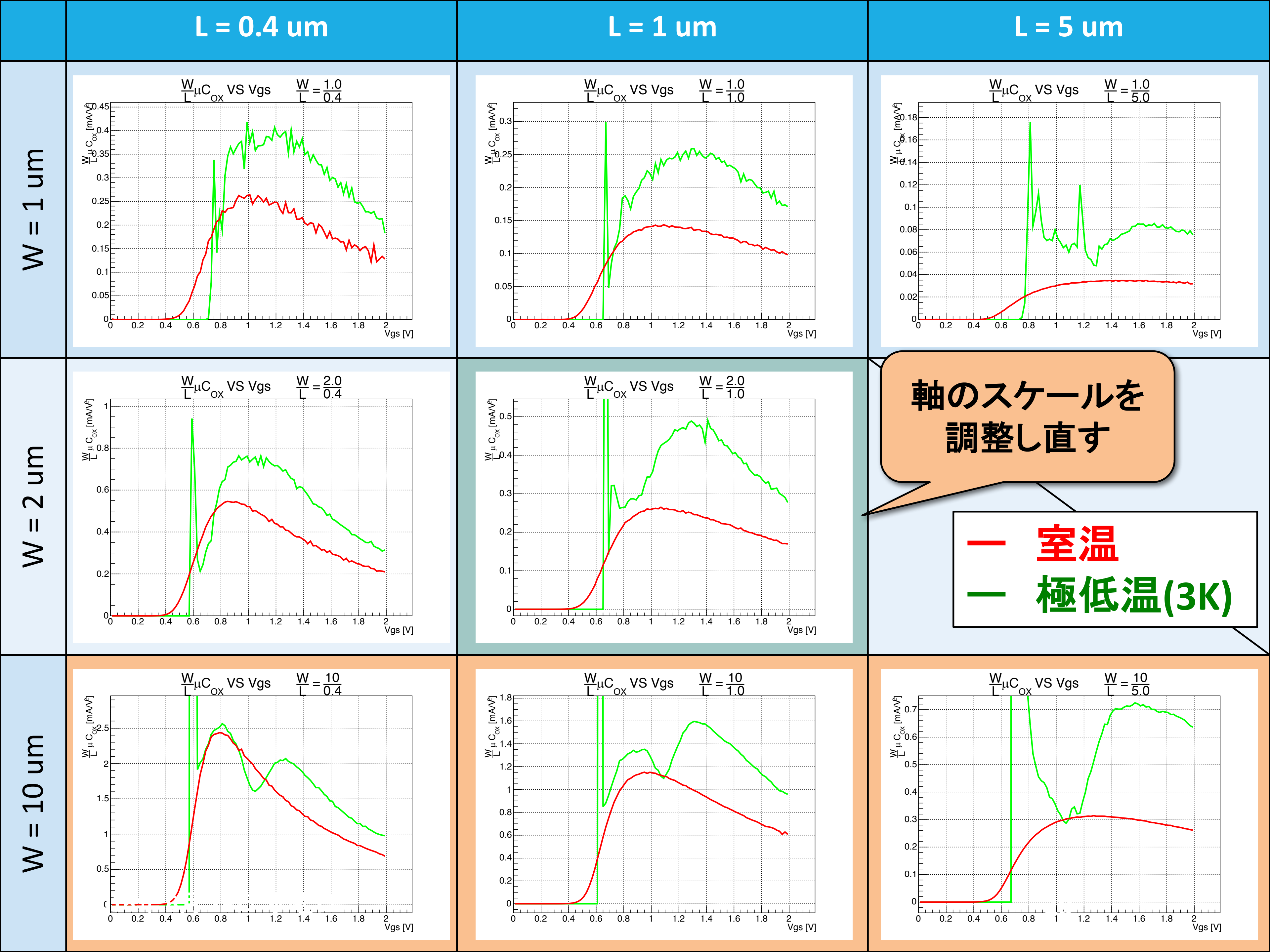
$$\begin{cases} I_{ds}(linear) = \mu C_{OX}\dfrac{W}{L}\{(V_{gs}-V_{th})V_{ds}-\dfrac{1}{2}{V_{ds}}^2\} \\ I_{ds}(saturated) = \mu C_{OX}\dfrac{W}{L}(V_{gs}-V_{th})^2 \end{cases}$$

この式を変形すると

$$\mu C_{OX}\frac{W}{L}(linear) = -\frac{\partial^2 I_{ds}}{\partial {V_{ds}}^2}$$

$$\mu C_{OX}\frac{W}{L}(saturated) = 2\left(\frac{\partial\sqrt{I_{ds}}}{\partial V_{gs}}\right)$$

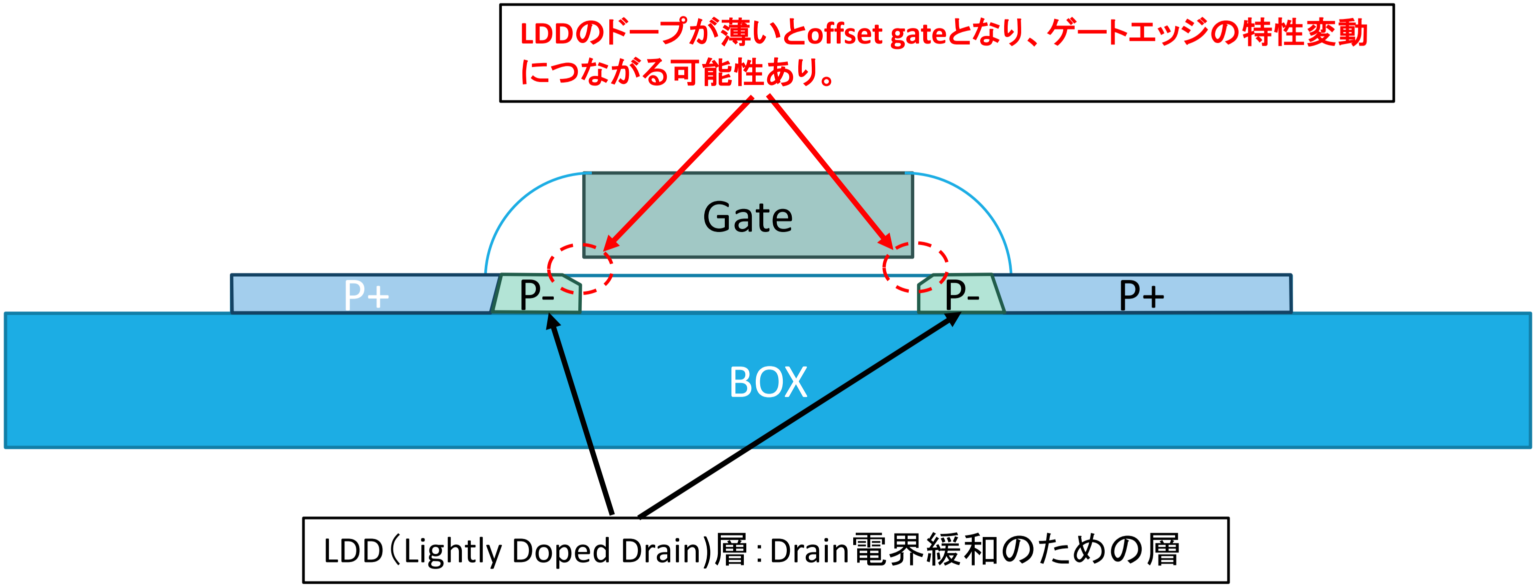
常温と3KでのuCW/Lの値の比がそのまま移動度の比


L = 0.4 um
L = 1 um
L = 5 um
W = 1 um
W = 2 um
W = 10 um
W/L μCox VS Vgs W/L = 1.0/0.4
W/L μCox VS Vgs W/L = 1.0/1.0
W/L μCox VS Vgs W/L = 1.0/5.0
W/L μCox VS Vgs W/L = 2.0/0.4
W/L μCox VS Vgs W/L = 2.0/1.0
W/L μCox VS Vgs W/L = 10/0.4
W/L μCox VS Vgs W/L = 10/1.0
W/L μCox VS Vgs W/L = 10/5.0
W/L μ Cox [mA/V²]
Vgs [V]
軸のスケールを
調整し直す
室温
極低温(3K)

LDD不純物濃度改良

LDD構造 : Lightly Doped Drain ・・・ ドレインとソースの間に低濃度の不純物領域を形成
→ドレインに高電界が生じるのを防ぐ

SPICE抽出のために測定したSOI-FETは、LDDのドープを薄くしたSOI-FETだったため、ゲートエッジ部の特性が変動し、Rdが異常に高くなる現象が見られた
→なので、ドープを濃くしたSOI-FETを極低温環境下で測定



LDD不純物濃度改良後のIV特性

ex.) Pch ST2　W/L = 10um / 1um

Ids VS Vds