# Development of Superconducting-Tunnel-Junction Single-Photon-Detectors Integrated with FD-SOI MOSFET Amplifiers

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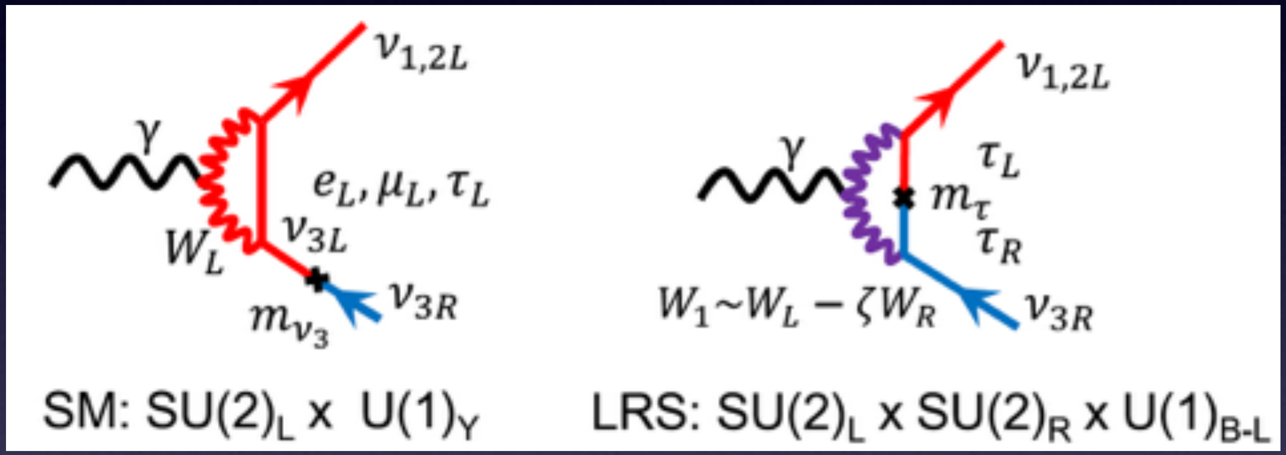
# Outline

- Search for the radiative neutrino decay
- The Superconducting Tunnel Junction (STJ)
- The Fully-Depleted Silicon-On-Insulator(FD-SOI) FET based cold amplifier
  - IV characteristics at cryogenic temperature
  - The capacitance of the STJ and readout line
  - The candidate design of cold amplifier for STJ
- Summary

# Neutrino radiative decay

Feynman diagrams for the neutrino radiative decay



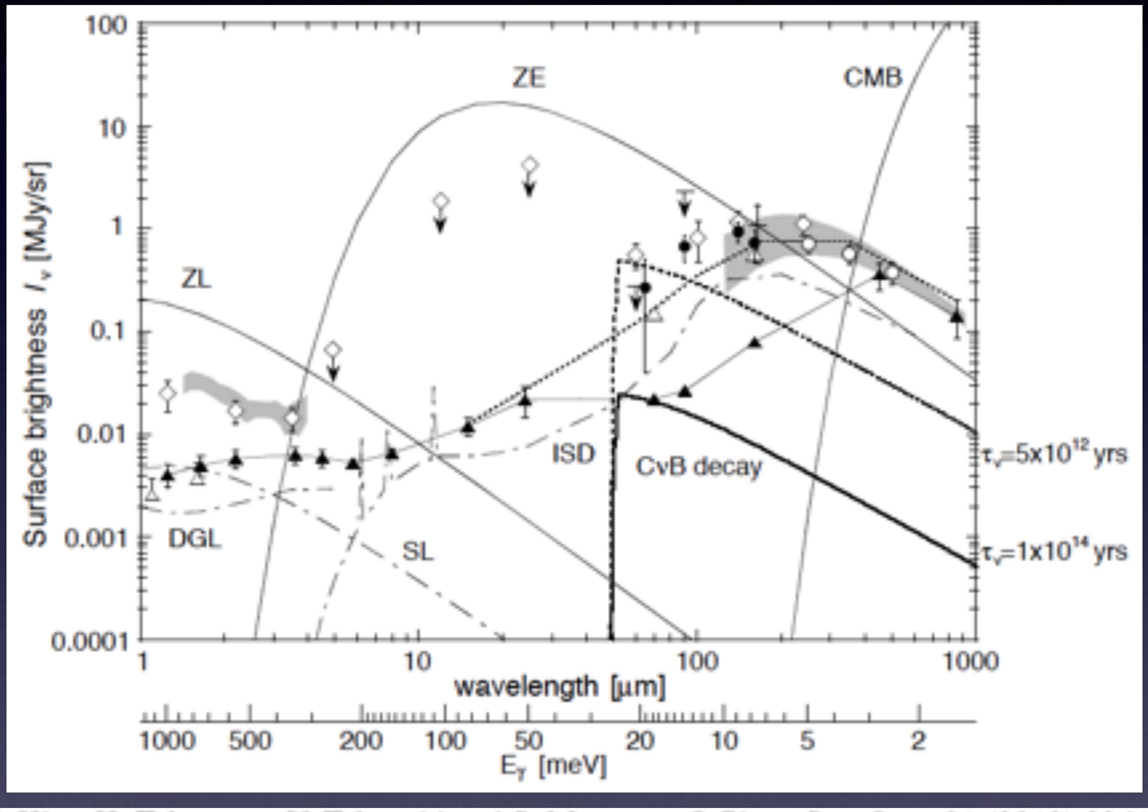

- Neutrinos have non-zero masses
  -> The heavy neutrino can decay into the light neutrino.

- The decay rate is drastically enhanced in the Left - Right symmetric model.

$$\tau_{SM} \approx 10^{43}\text{years} \qquad \tau_{LRSM} \approx 10^{17}\text{years}$$

- The cosmic neutrino background(CvB) is a good neutrino source for the neutrino radiative decay search.

# Search for the CvB decay




S. H. Kim, K. Takemasa, Y. Takeuchi and S. Matsuura, J. Phys. Soc. Jpn., 81 (2012) 024101S

Shape of CvB decay signal

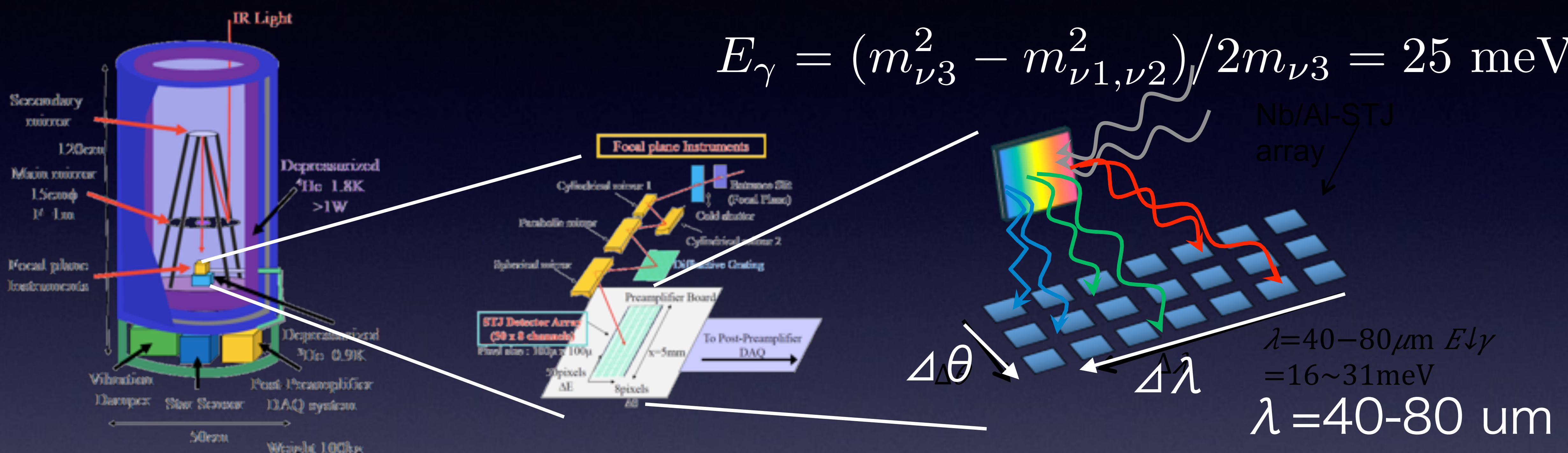
Monochromatic photon
+ Red shift

This well known shape is useful
to pick up the signal
from the Zodiacal Emission(ZE)

- The energy of photon is expected to be 40um-80um
- The current experimental lower limit is $\tau_{\nu 3} = 3 - 4 \times 10^{12}$ years
- Target of our next experiment is $\tau_{\nu 3} = 10^{14}$ years
- We plan to measure the continuous distribution of the photon energy

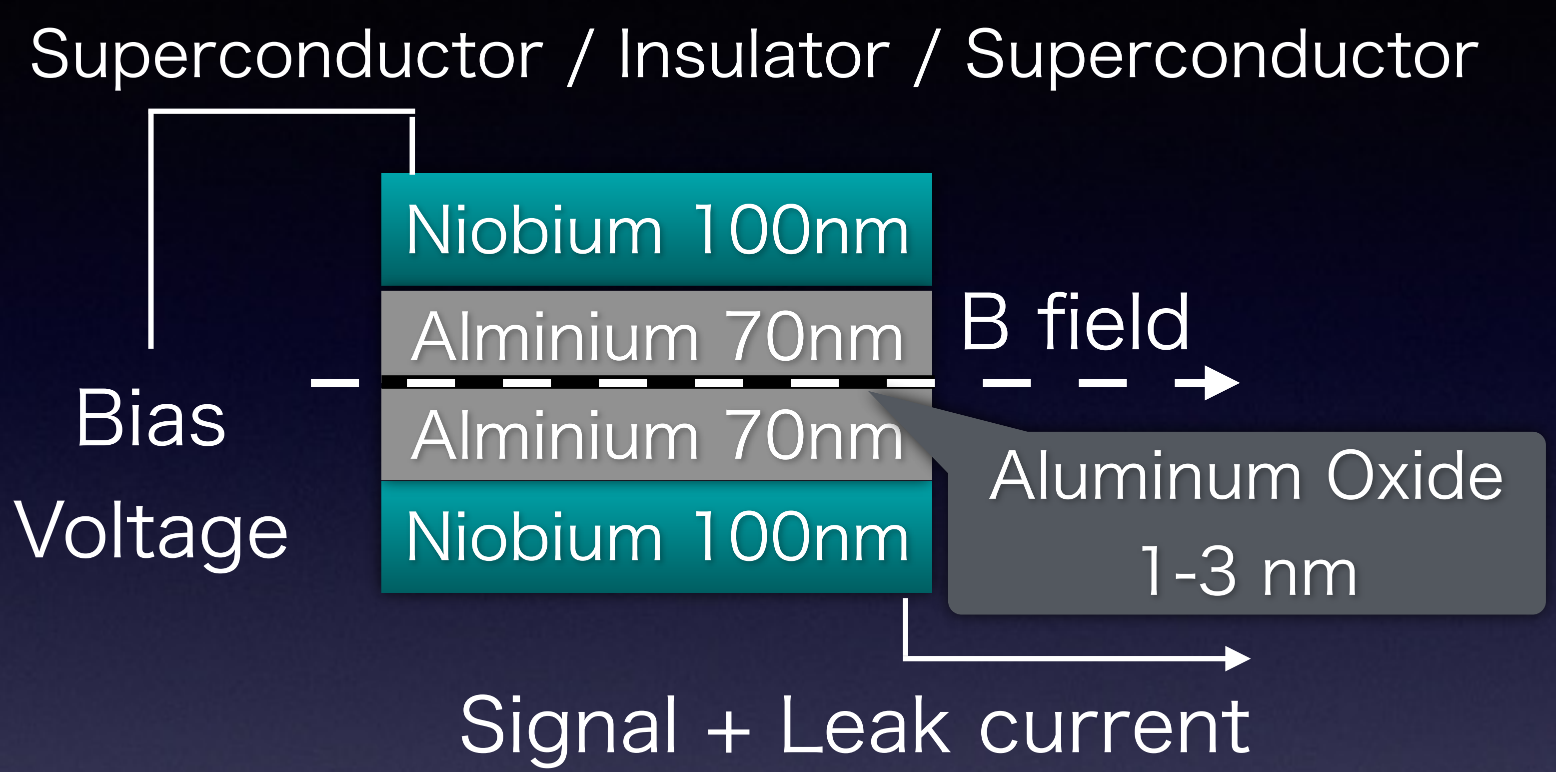
# CvB rocket experiment

$$E_\gamma = (m_{\nu 3}^2 - m_{\nu 1,\nu 2}^2)/2m_{\nu 3} = 25 \text{ meV}$$




- Expected observation period is 200sec at an altitude of 200-300km
  - The telescope with diameter of 15cm and focal length of 1m
- The diffraction grating(40-80um) with ⊿λ x⊿θ =50x8 STJ pixels
- Detectors must be able to count the single FIR photon with sampling rate of 500kHz to suppress the background due to the dark noise
- Requirements: $Q_{noise} < 30e$ for $2\mu$s integration, $\mathrm{I}_{\mathrm{dark}} < 0.1\mathrm{nA}$

# The Superconducting Tunnel Junctions(STJ)

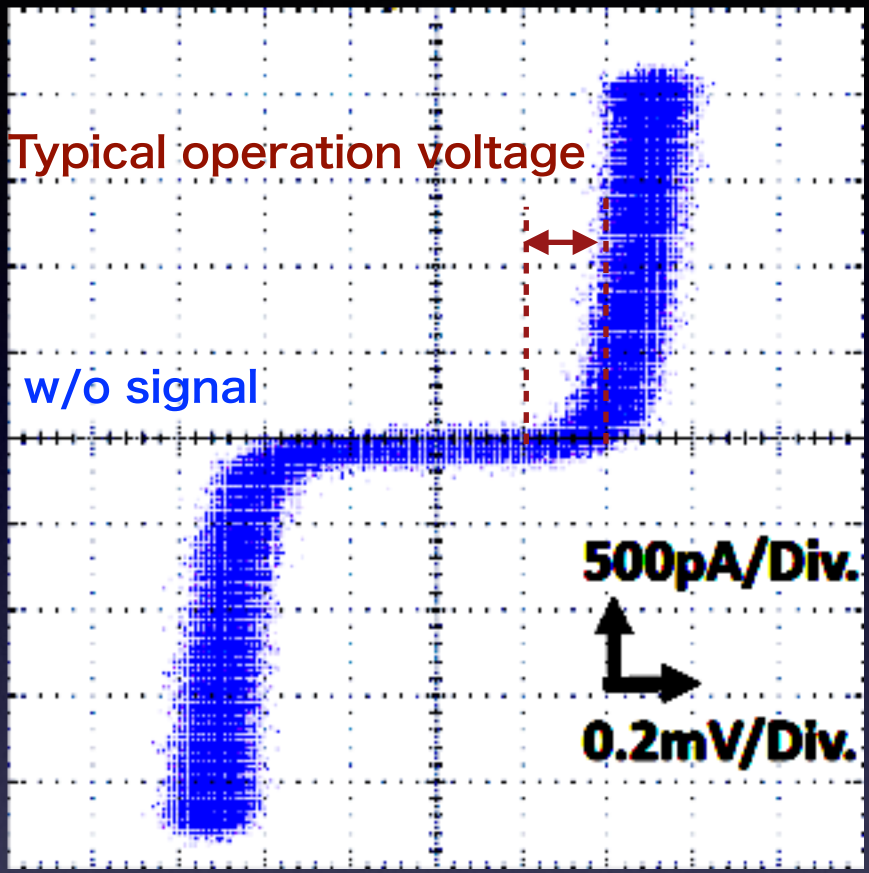


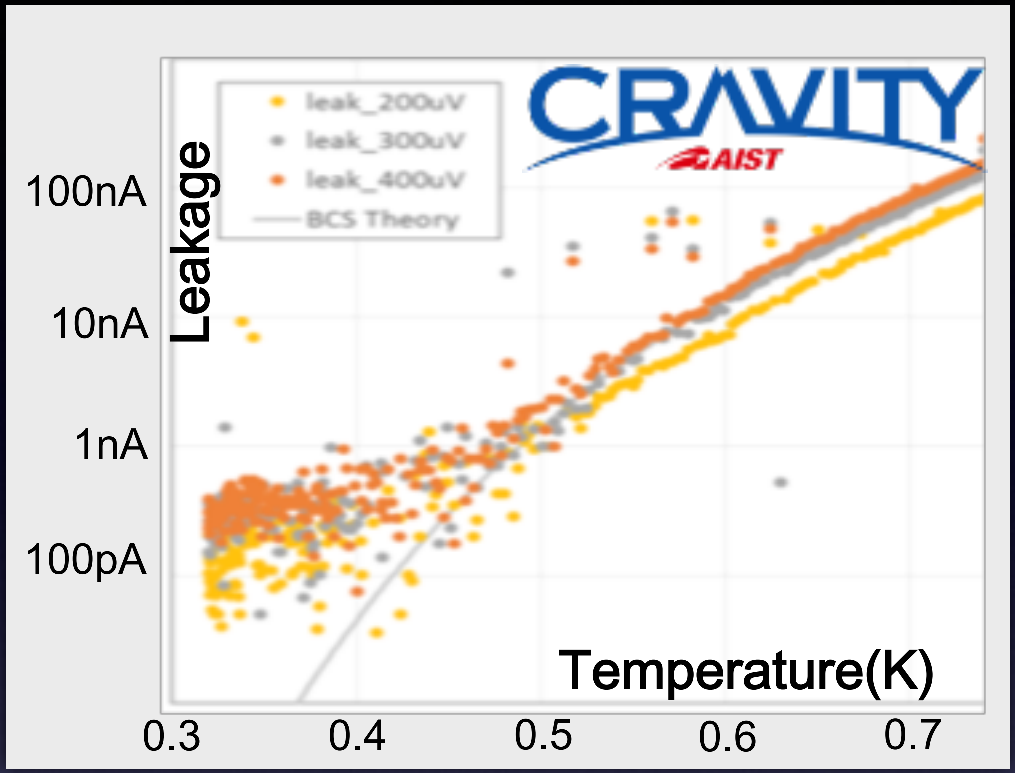

| | Al | Nb | Si |
|---|---|---|---|
| Energy gap (meV) | 0.172 | 1.55 | 1100 |
| Critical temperature (K) | 1.2 | 9.2 | - |

The Nb/Al bi-layer has an energy gap and Tc between pure Nb and Al (proximity effect)

- The superconductor has a tiny band-gap
- The number of excited electron is proportional to the deposited energy. Ne=E/1.7⊿
- The response time is a few us
  - Suitable for single photon detection
- Insulation layer must be thin, since STJ is a tunnel device
  - STJ have an large capacitance with a high leak current

# The IV characteristic of Nb/Al-STJ



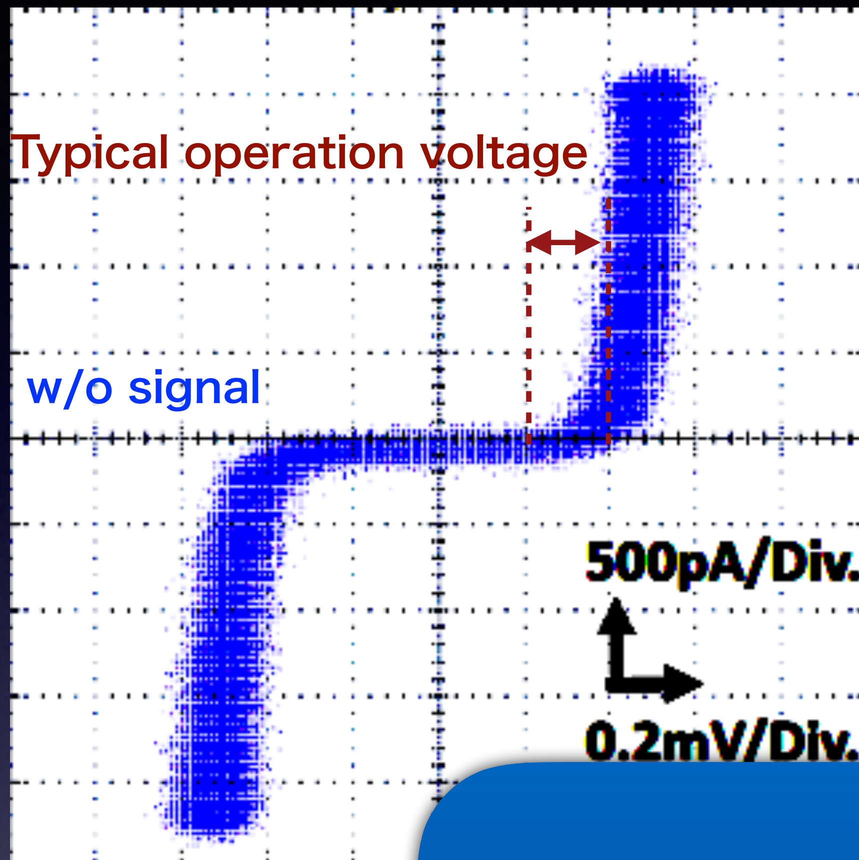

M. Ukibe et al., Jpn. J. Appl. Phys. 51, 010115 (2012)
M. Ohkubo et al., IEEE Trans. Appl. Super, 24, 2400208 (2014)

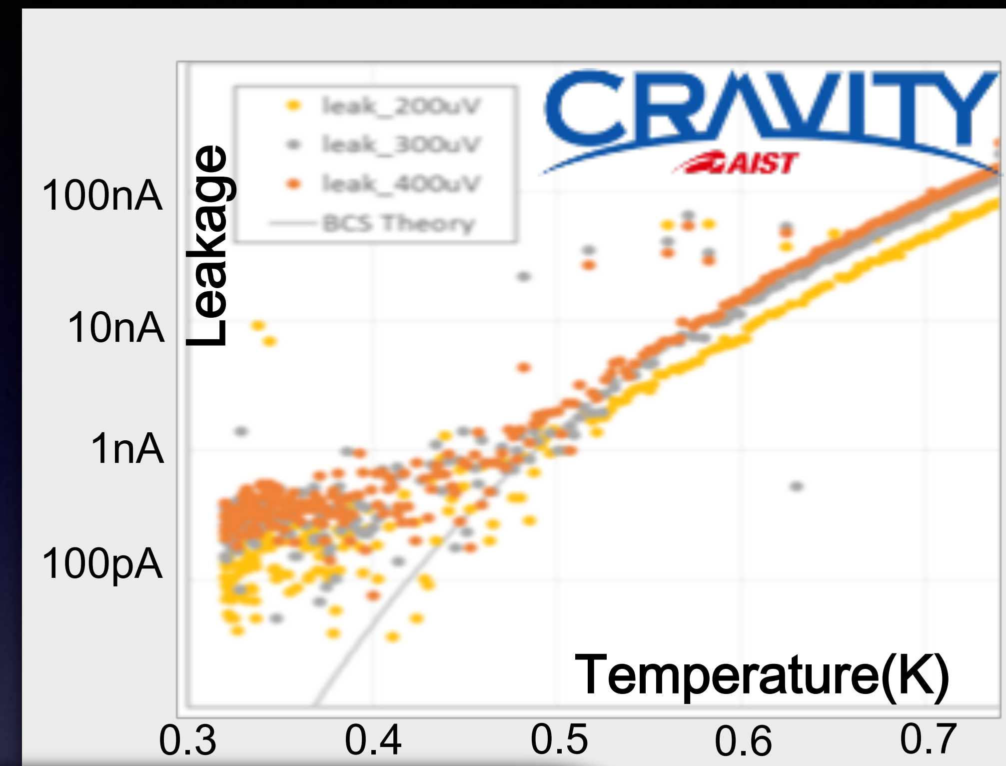
- Nb/Al/AlOx/Al/Nb-STJ processed at CRAVITY(*) exhibited excellent quality

  *the clean room for analog-digital superconductivity

  - Leakage currents of STJs( $50 \times 50 \mu m^2$ ) are less than 500pA
- Thicknesses of Nb/Al bi-layer are optimized for the 3He refrigerator
  - The band-gap of this device is ⊿ = 0.6 mV, operation temperature < 370 mK
  - x5-10 larger signal compared to pure Nb-STJ

# The IV characteristic of Nb/Al-STJ




51, 010115 (2012)

Super, 24, 2400208 (2014)

**Detail will be reported by Koya's talk on the 3rd of Dec**

- Nb/Al/AlOx/Al/N … cellent quality
  … superconductivity
  - Leakage curre … pA
- Thicknesses of Nb/Al bi-layer are optimized for the 3He refrigerator
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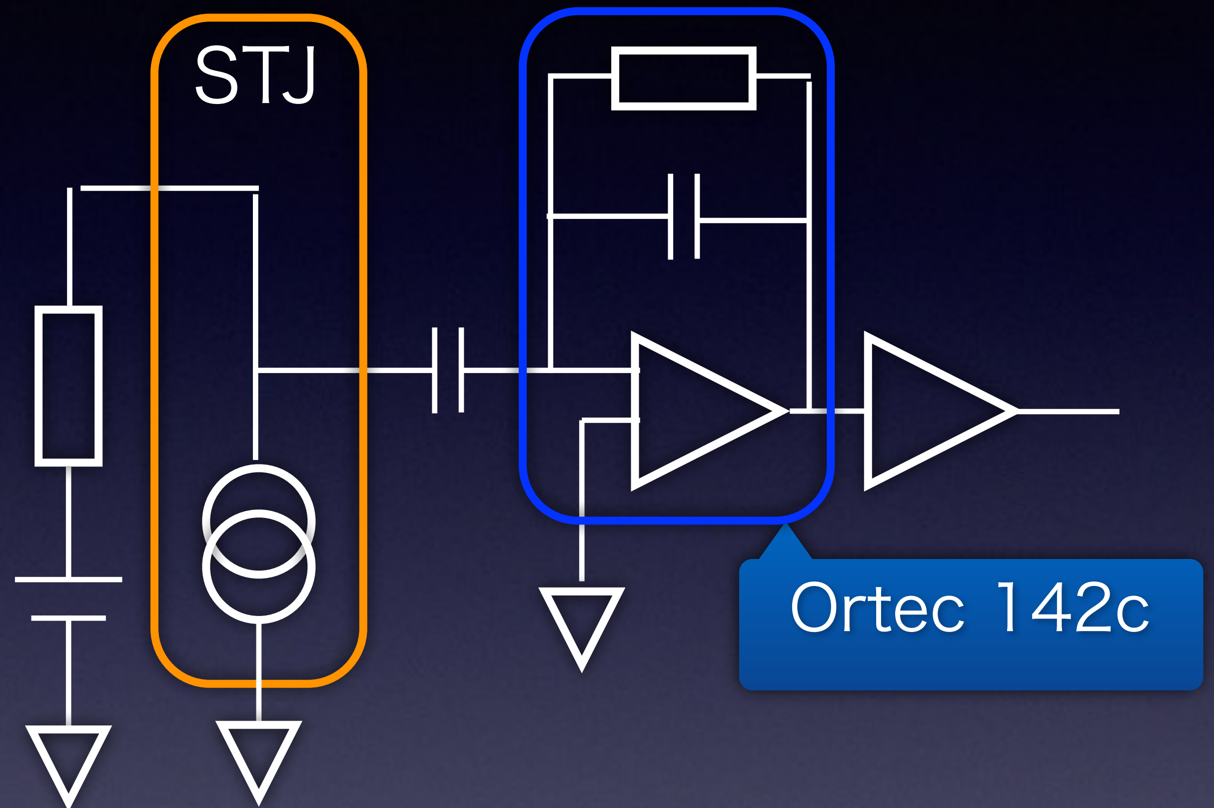
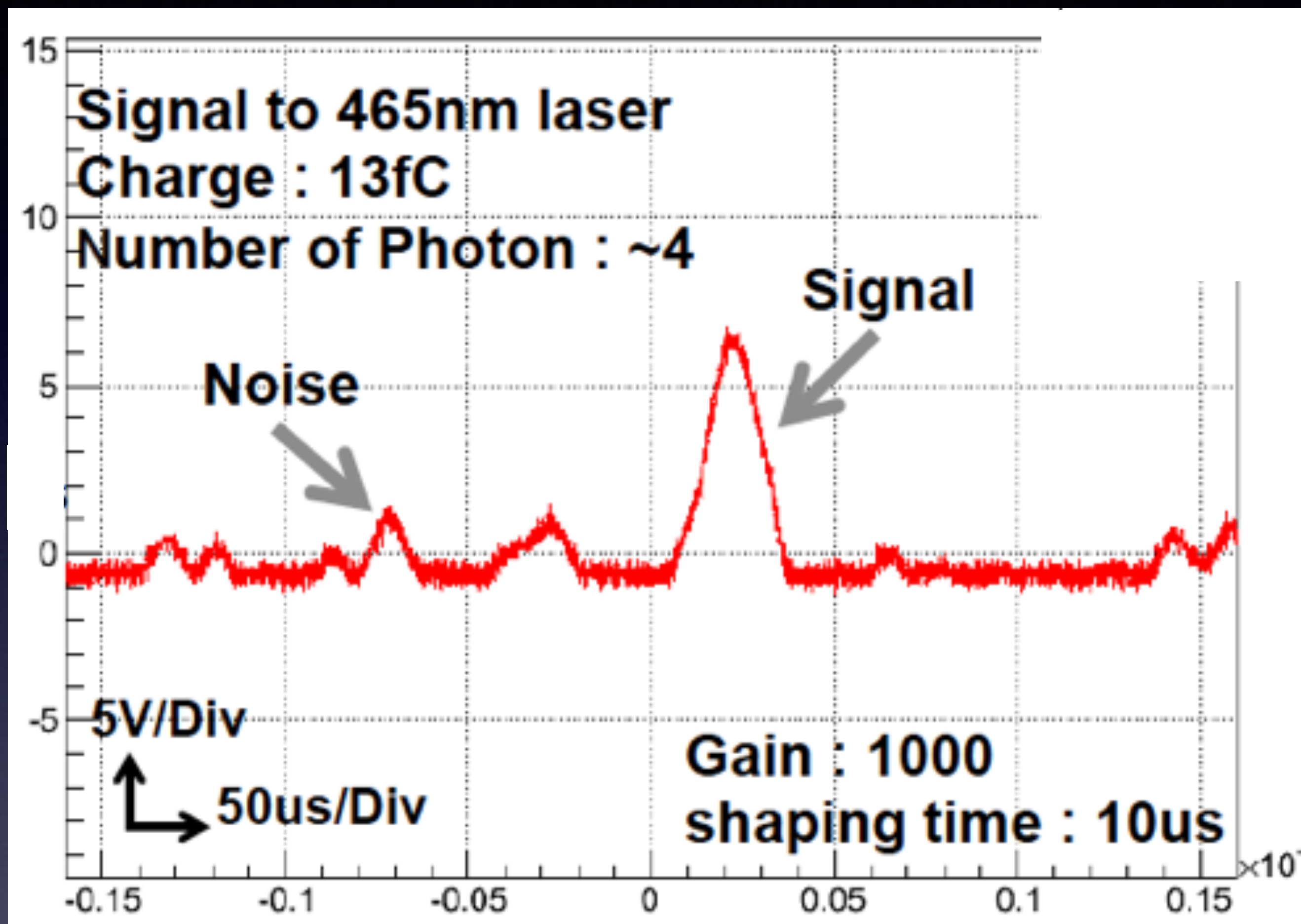
# The readout circuit for STJ

3He refrigerator



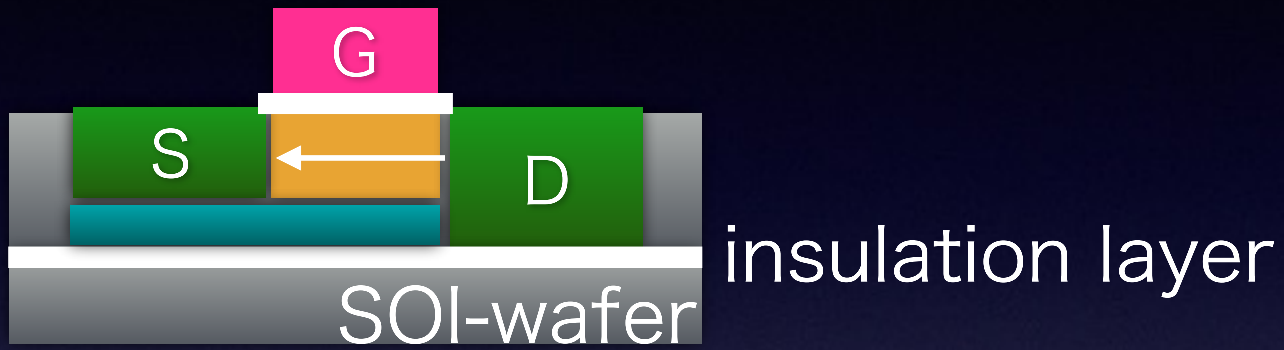




The output of the STJ for 465nm photon with ordinary amplifier

The cold amplifier is a best solution to solve the following issues

- The transmission loss due to long readout line
- Thermal noises of readout line and amplifier
- Electromagnetic noises from environment

# Fully-Depleted Silicon-On-Insulator technology



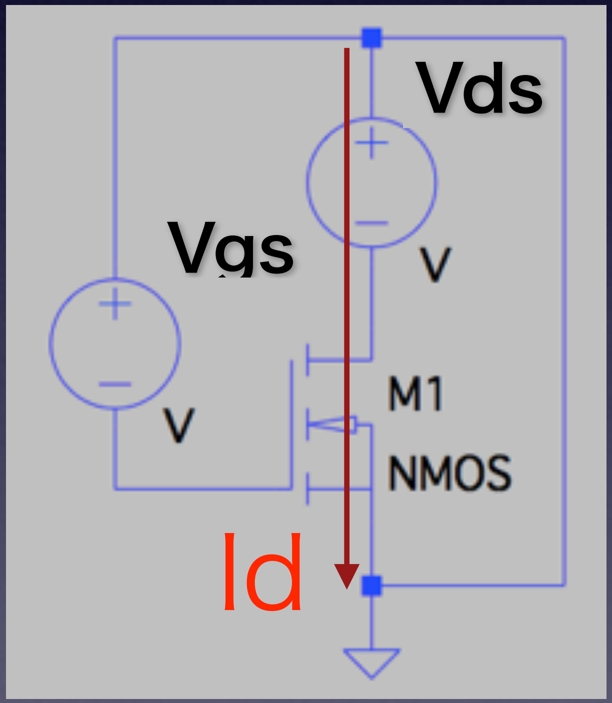

- Fabricated by Lapis semiconductor 0.2um FD-SOI process
- FD-SOI FET: Low noise and low power dissipation
- The source body tie structure(ST) of the FD-SOI FET
  - The body is connected with the source to stabilize body potential
- This FET shows an excellent performance at 4.2 K (*)

* H. Nagata et al. AIP conference proceedings, vol.1185, pp267-270,2009

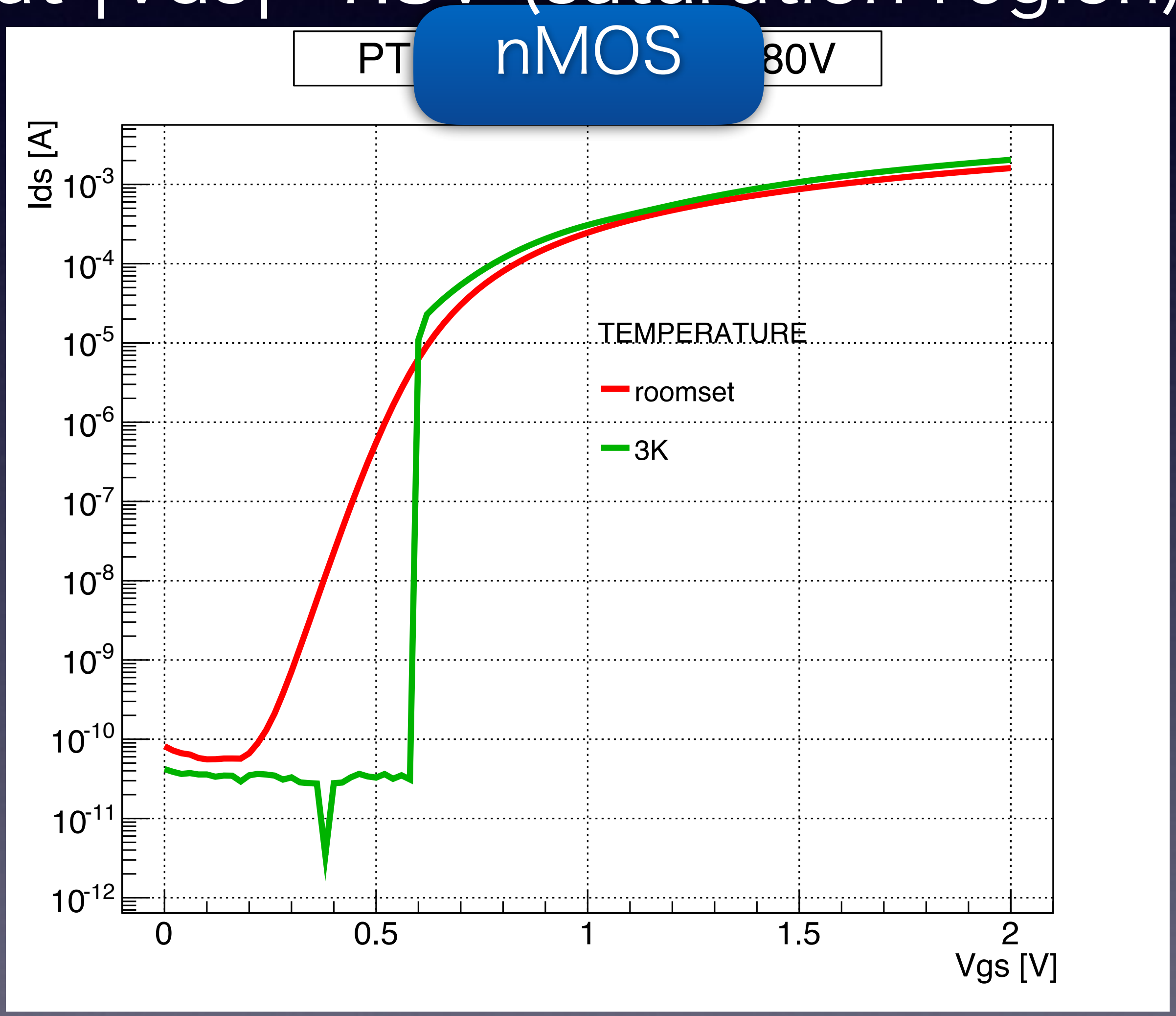
- We confirmed that the FD-SOI FETs operate at 100 mK

# Id-Vg characteristics

Vds is fixed, when
Ids is plotted as a function of Vgs



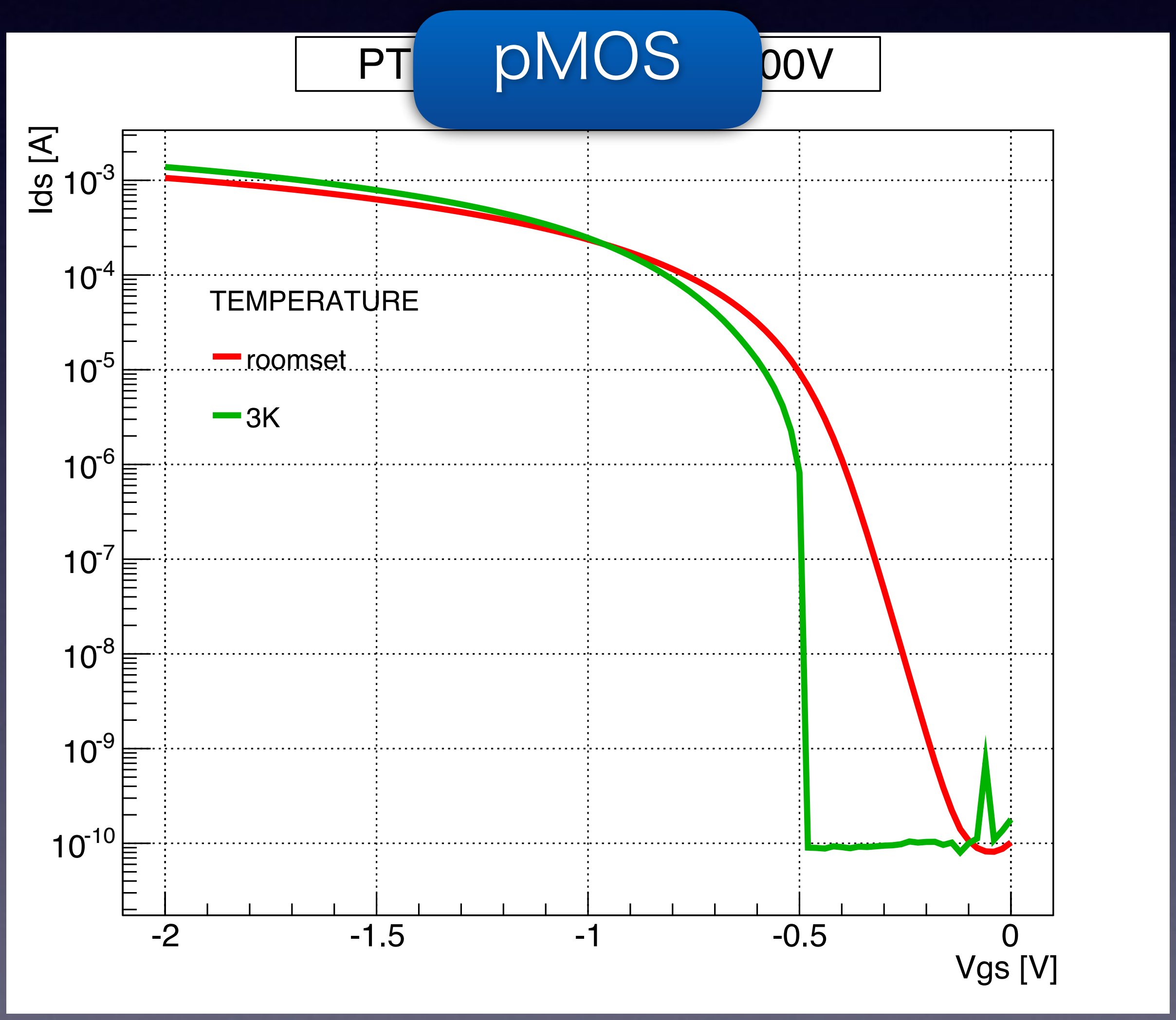

Id-Vg curve of W/L=10um/0.4um
at |Vds|=1.8V (saturation region)

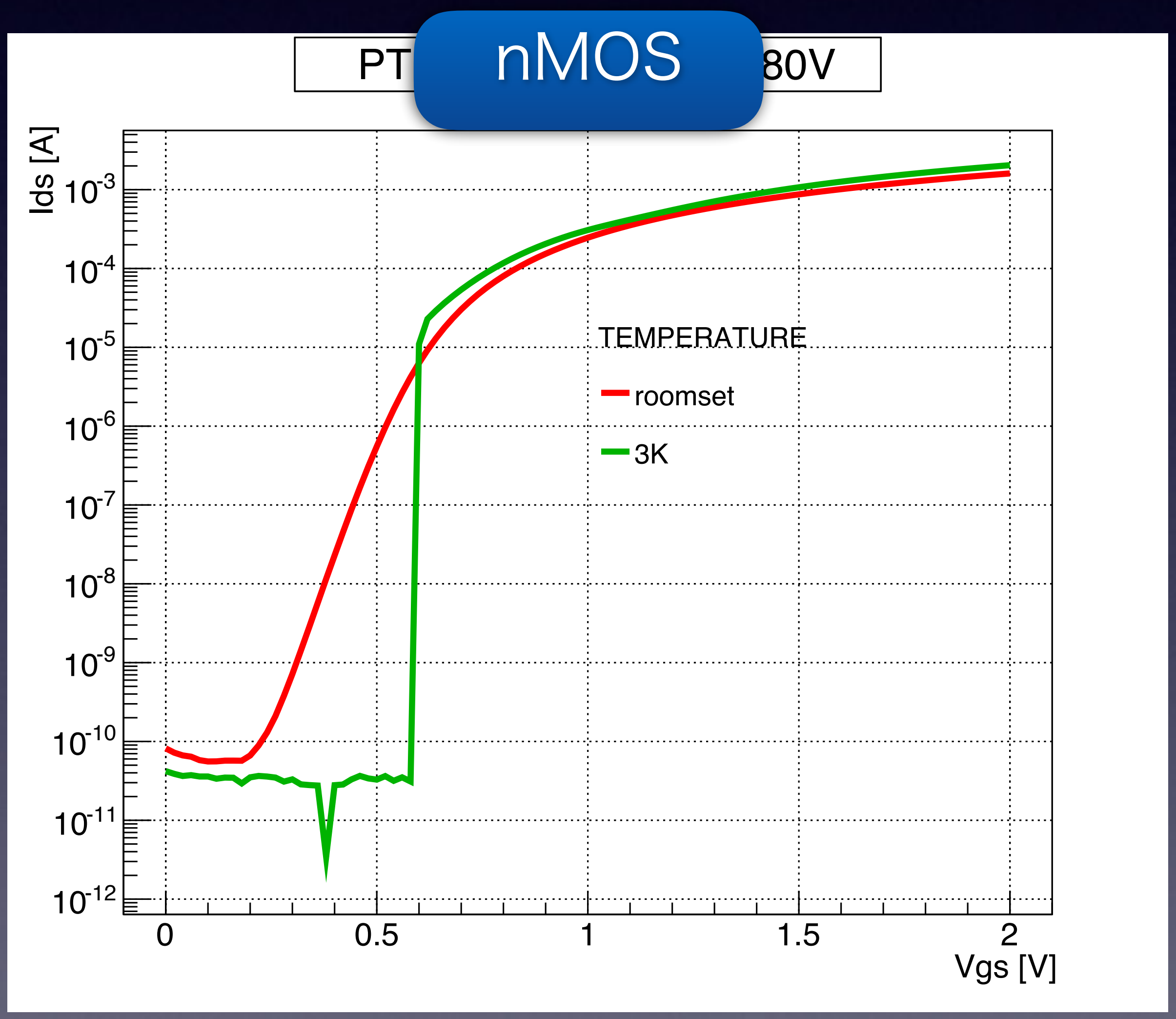



Generally, the FET turns on at typical voltage
The slope of curve(trans conductance) correspond to a gain of amp

# FD-SOI FET Id-Vg curve

Id-Vg curve of W/L=10um/0.4um at |Vds|=1.8V (saturation region)




Both pMOS and nMOS show excellent performances at 3K

Increasing the threshold and mobility of the carrier

# Id-Vd characteristics

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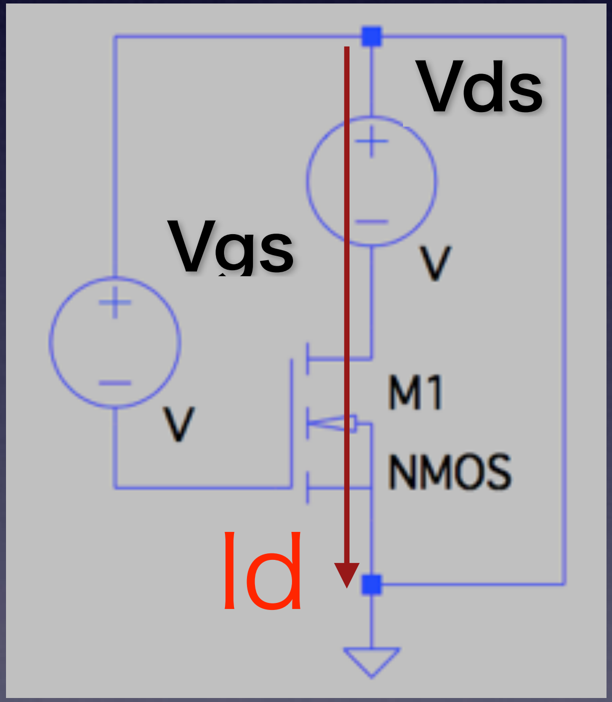
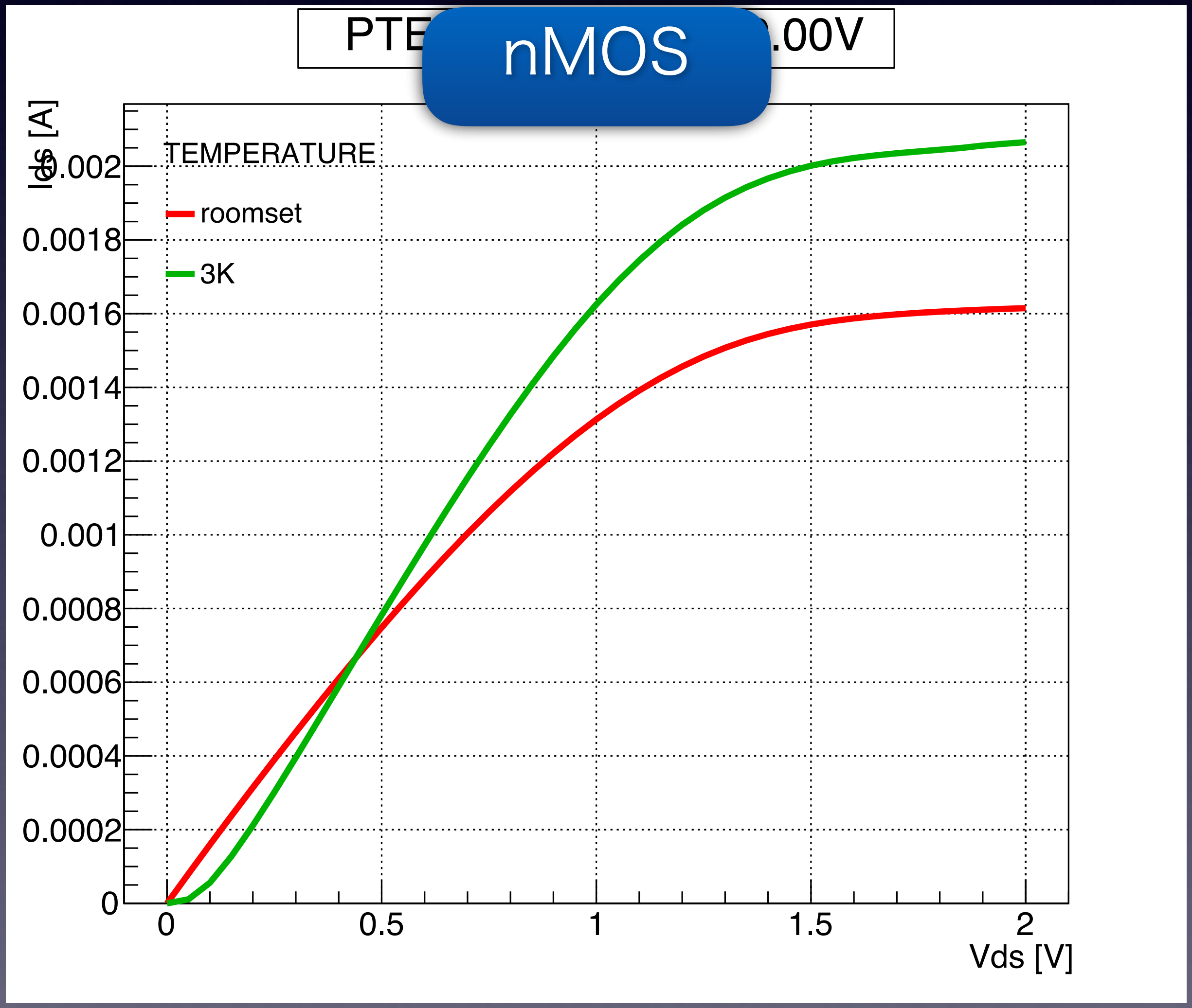


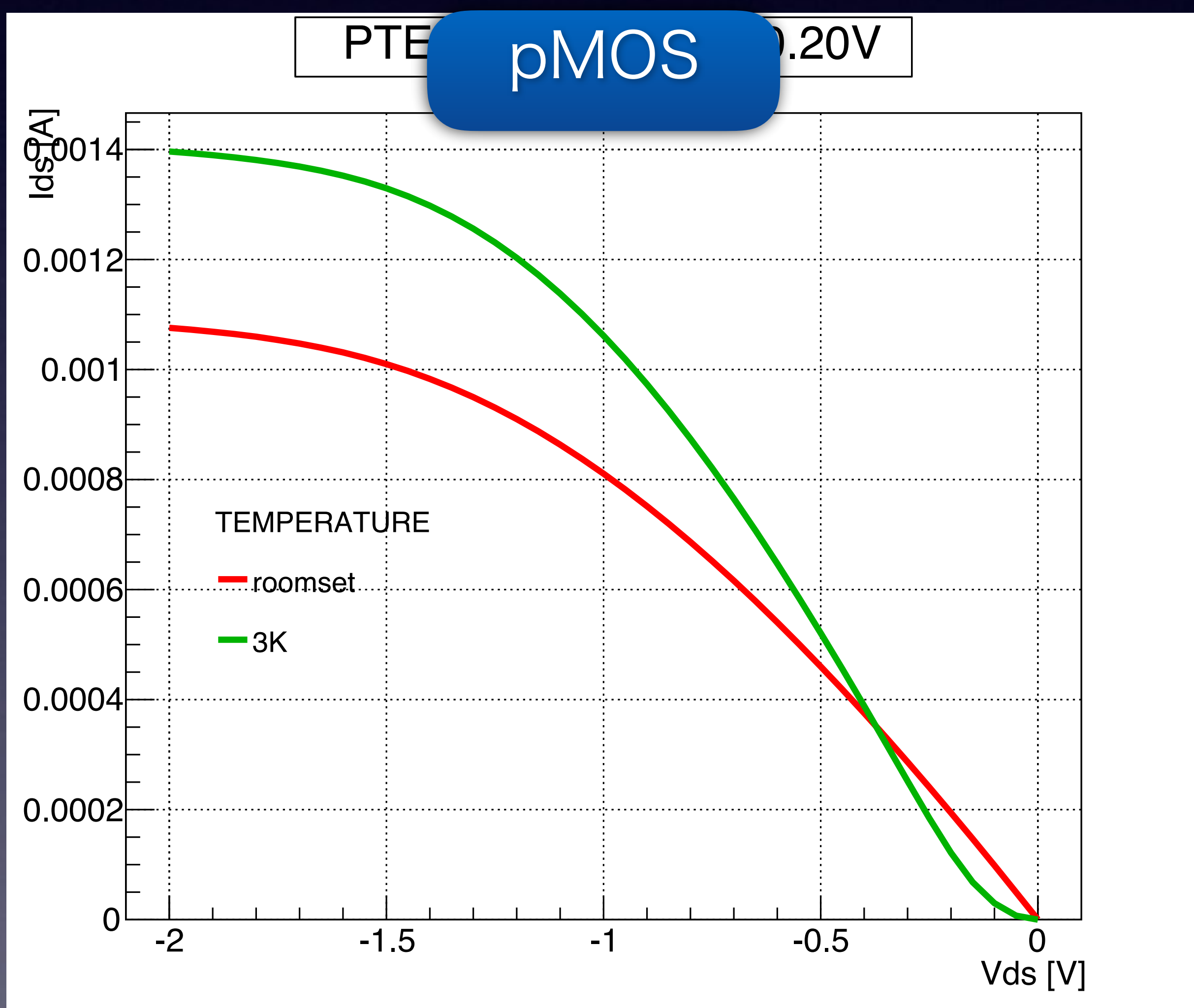

Id-Vg curve of W/L=10um/0.4um
at |Vgs|=2V

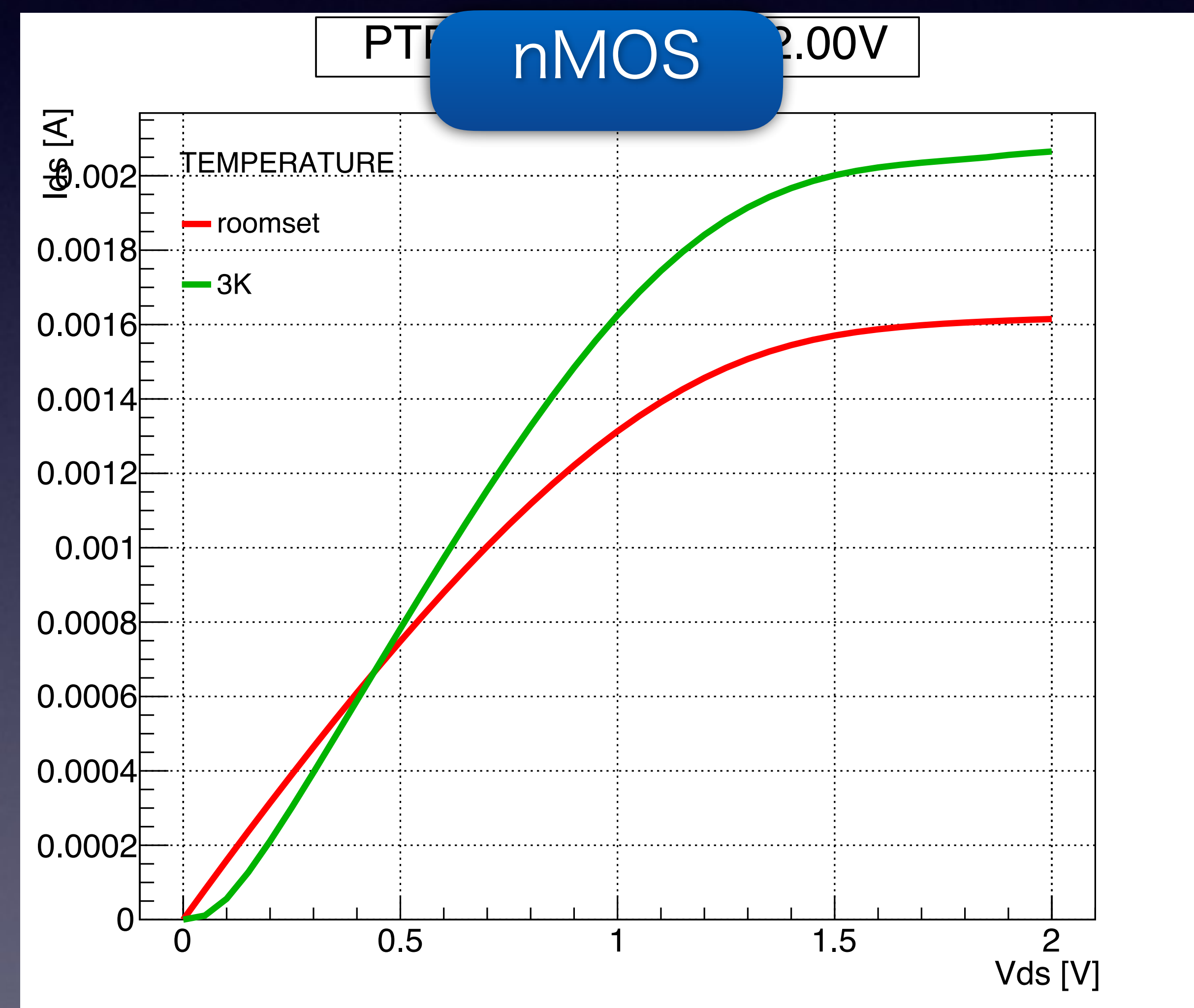



The Vds > Vds-Vth region called saturated region
The FET acts as constant current source at this region

# FD-SOI FET Id-Vd curve

Id-Vg curve of W/L=10um/0.4um at |Vgs|=2V



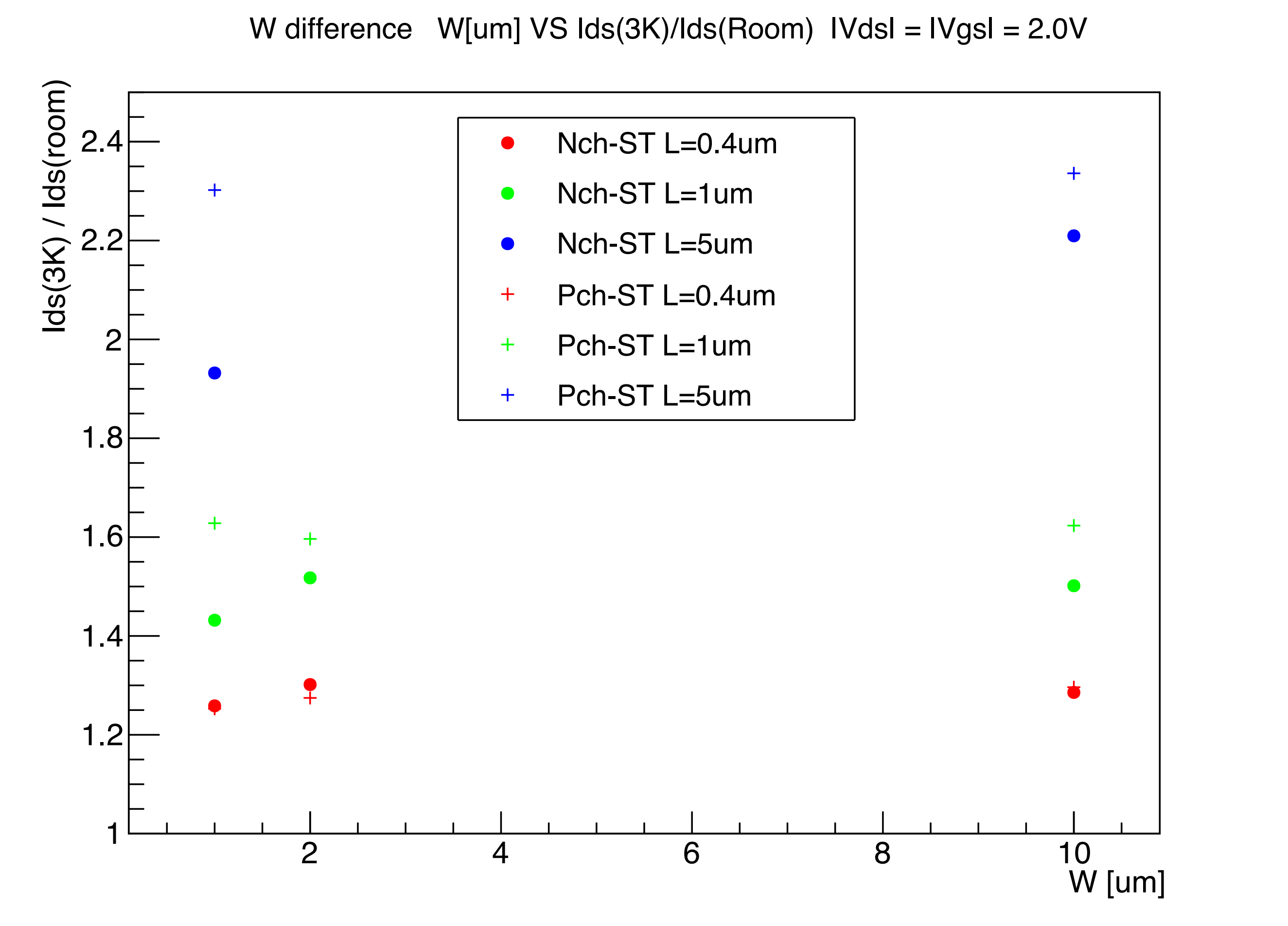

Non linear shapes are observed around Vds=0 V

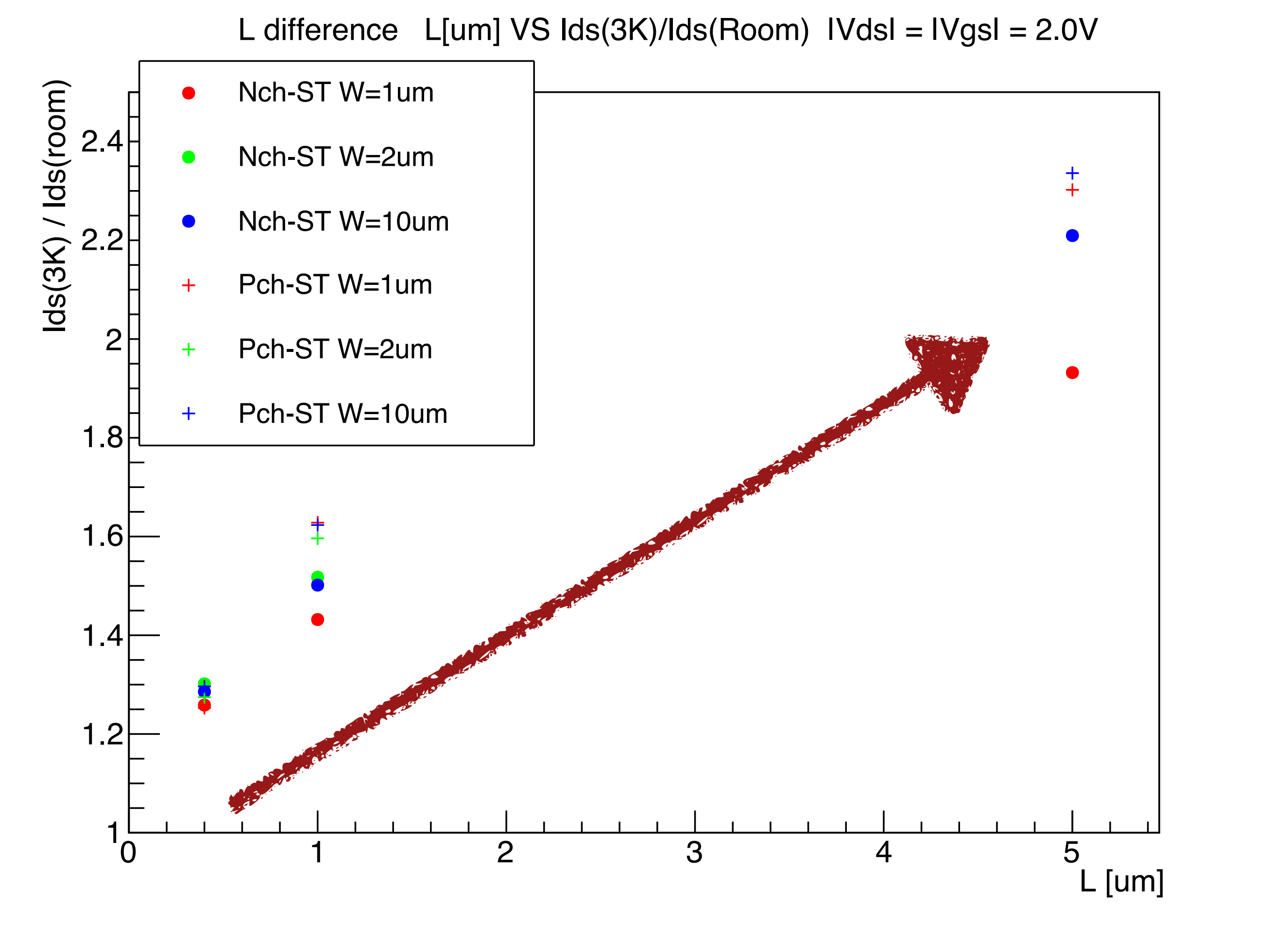
The LDD structure could explain this phenomena(under investigation)

Our circuits uses only saturated region of FETs

# The size dependence of the Id

- Measured W and L range: W=1-10um and L=0.4-5um




Id ratio(3K/300K) is independent to the W of FET,

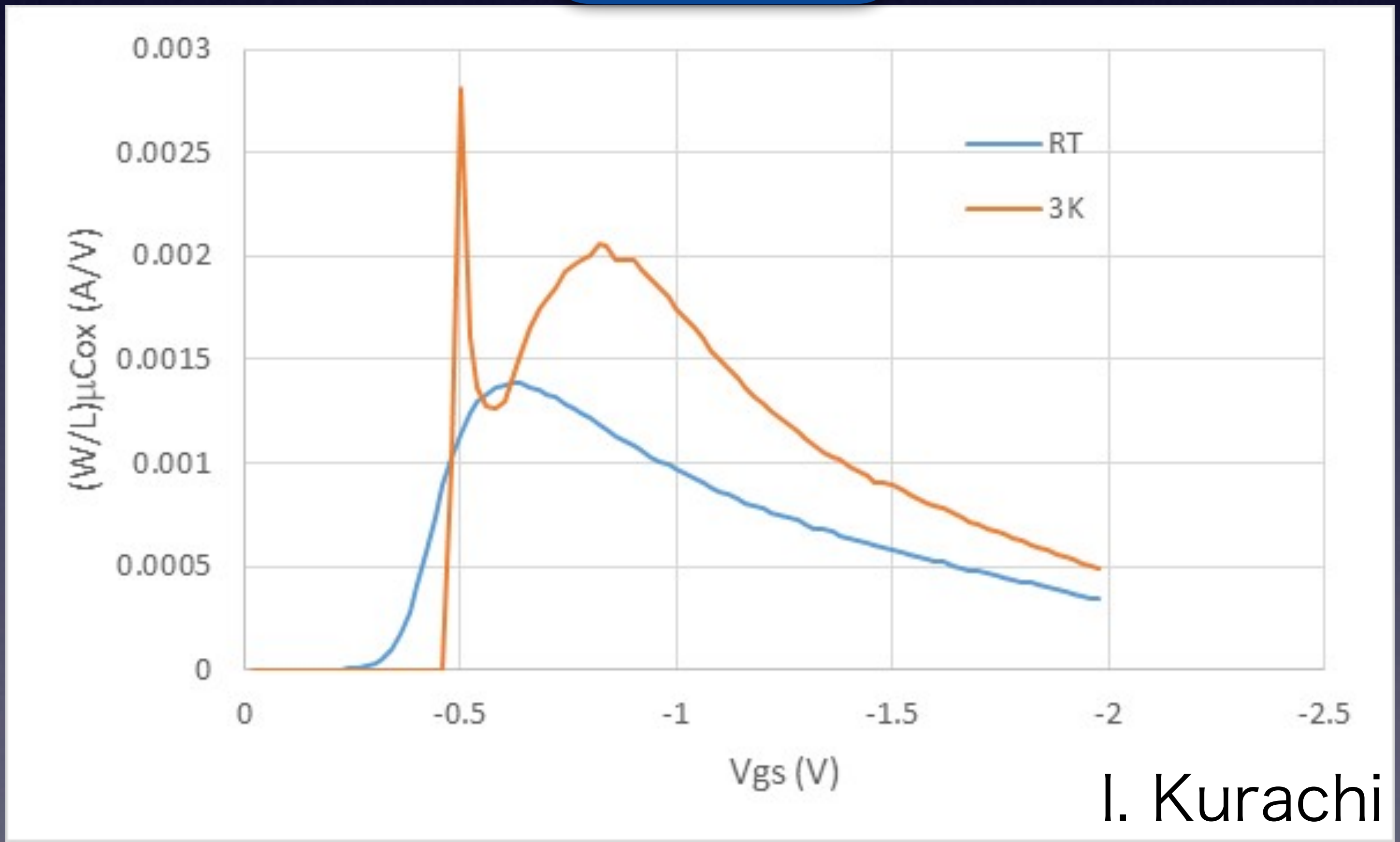
while it has L dependency.

Larger L devices show large ratio

# Mobility of carriers @3K

$$I_{d_{sat}} = \frac{1}{2}\frac{W}{L}\mu C_{ox}(V_{gs} - V_t)^2 \rightarrow \mu \propto (\frac{\partial\sqrt{I_{d_{sat}}}}{\partial V_{gs}})^2$$

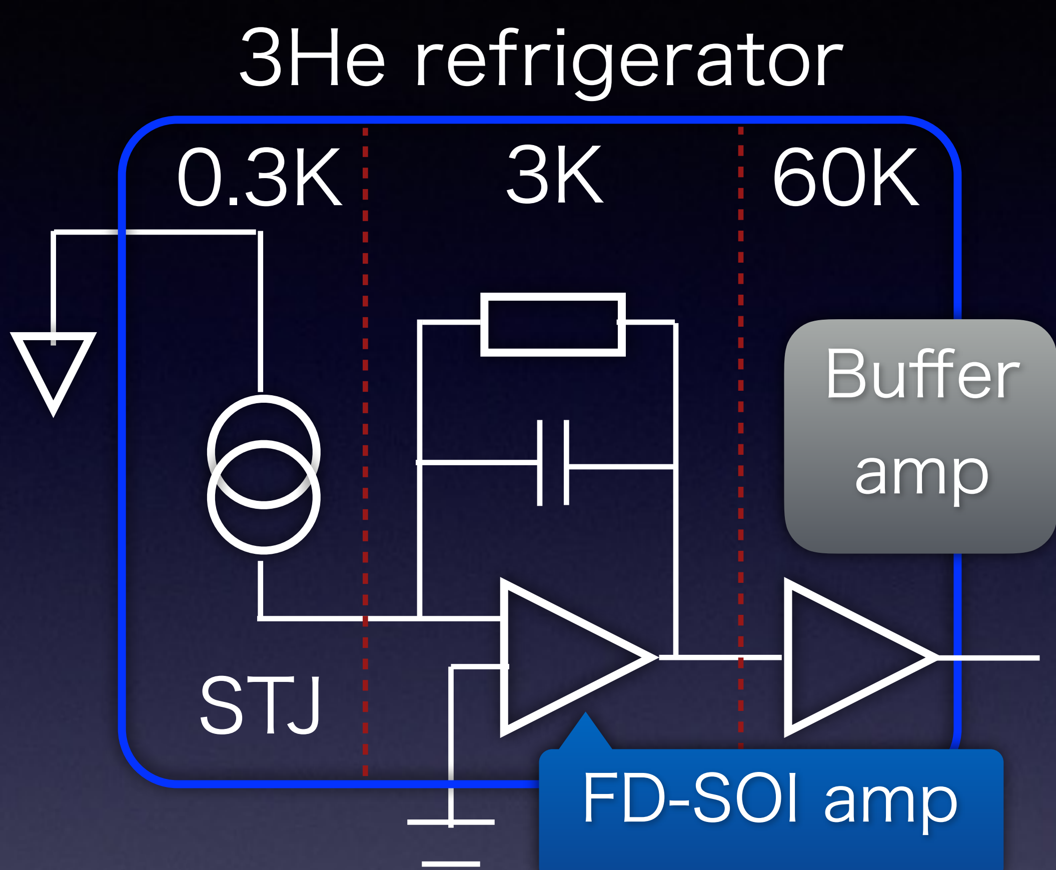
pMOS

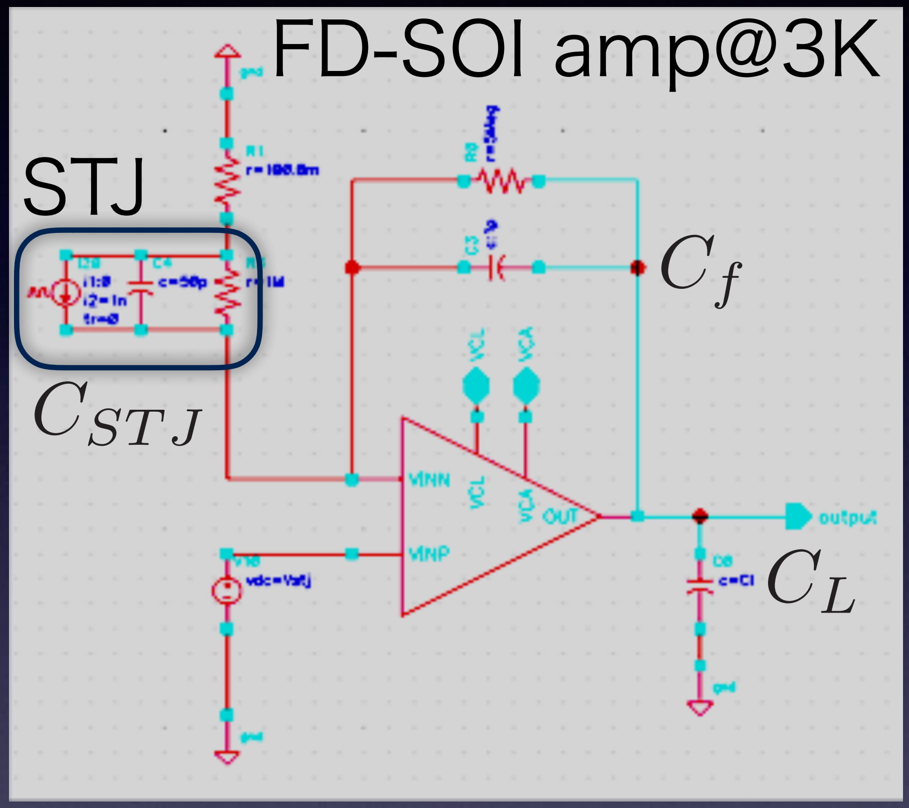



Mobility of the carriers increase x1.5 at 3K

We investigate the cause of first peak

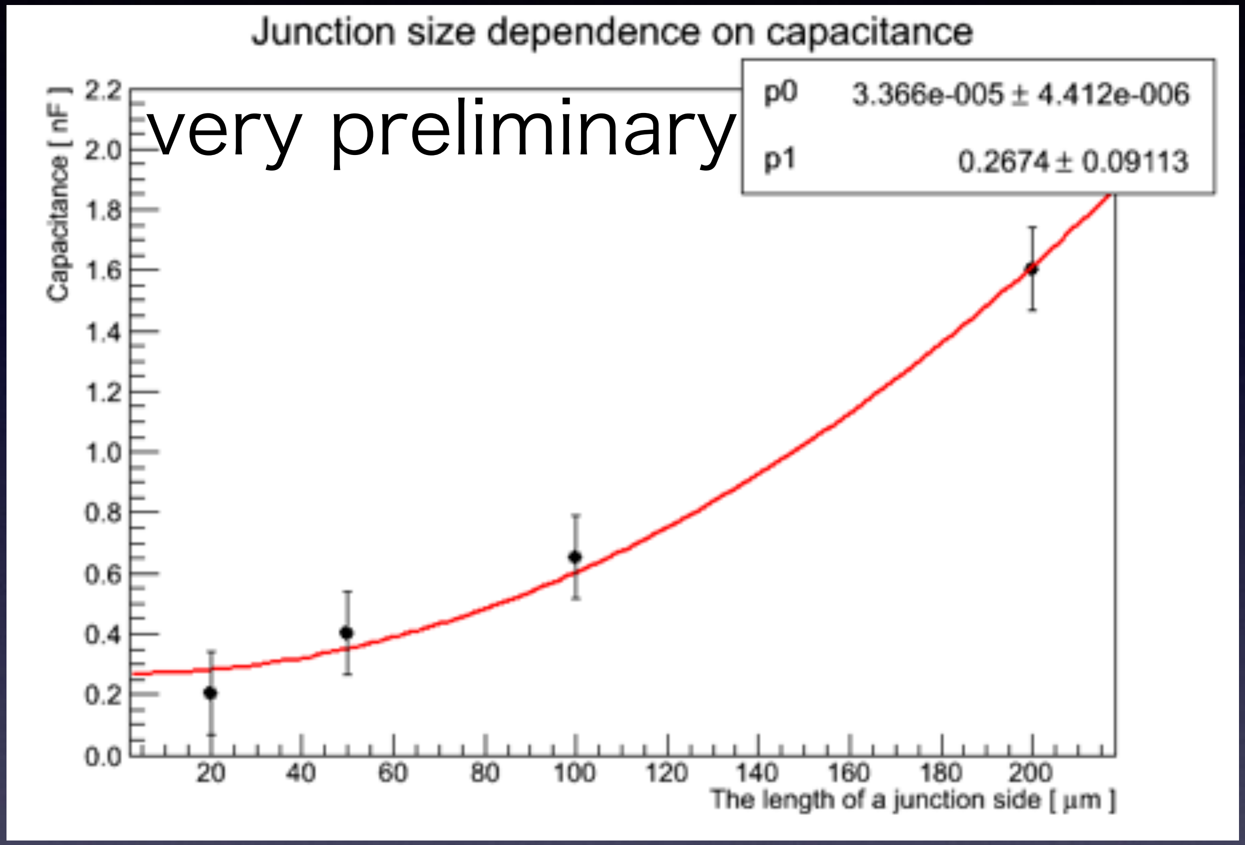
# Design of the readout circuit




- There are three stages in 3He refrigerator: 300mK, 3K and 60K
- The STJ is operated on 300mK stage
- The FD-SOI pre-amplifier is operated on 3K stage
- The buffer amplifier drives high load capacitance at 60K
- First target of this circuit is 1.3um single photon counting

# Capacitance of the STJ

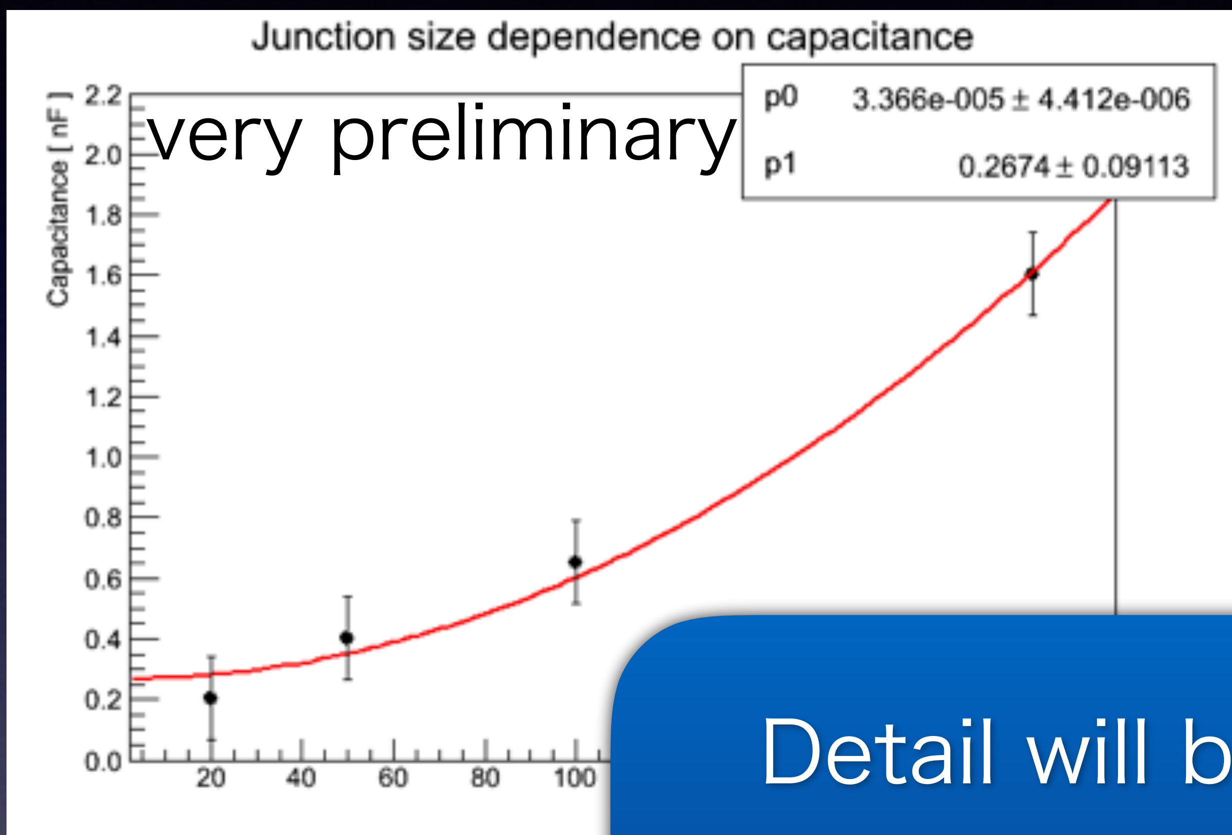



If we assume the capacitance of STJ depends on only the area of STJ

$$C_{all} = C_{RO} + C_{STJ} \times Length^2$$
$$C_{RO} : \ Cap.\ of\ readout\ line$$
$$C_{STJ} : \ Cap.\ of\ STJ\ in\ unit\ area$$

- Capacitance of the readout line(0.8nF) is already subtracted
- Capacitance of the STJ is estimated to be $C_{STJ}(\mathrm{nF}) = (3.4\pm0.4) \times \mathrm{Area}(\mu\mathrm{m}^2)$
- Parasitic capacitance in the readout line(300mK->300K) is $1.1 \pm 0.1\ \mathrm{nF}$
- Capacitance of $20 \times 20 \mu m^2$ STJ is expected to be $14 \pm 2\ \mathrm{pF}$

# Capacitance of the STJ

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$C_{RO}$ : *Cap. of readout line*

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Detail will be reported by
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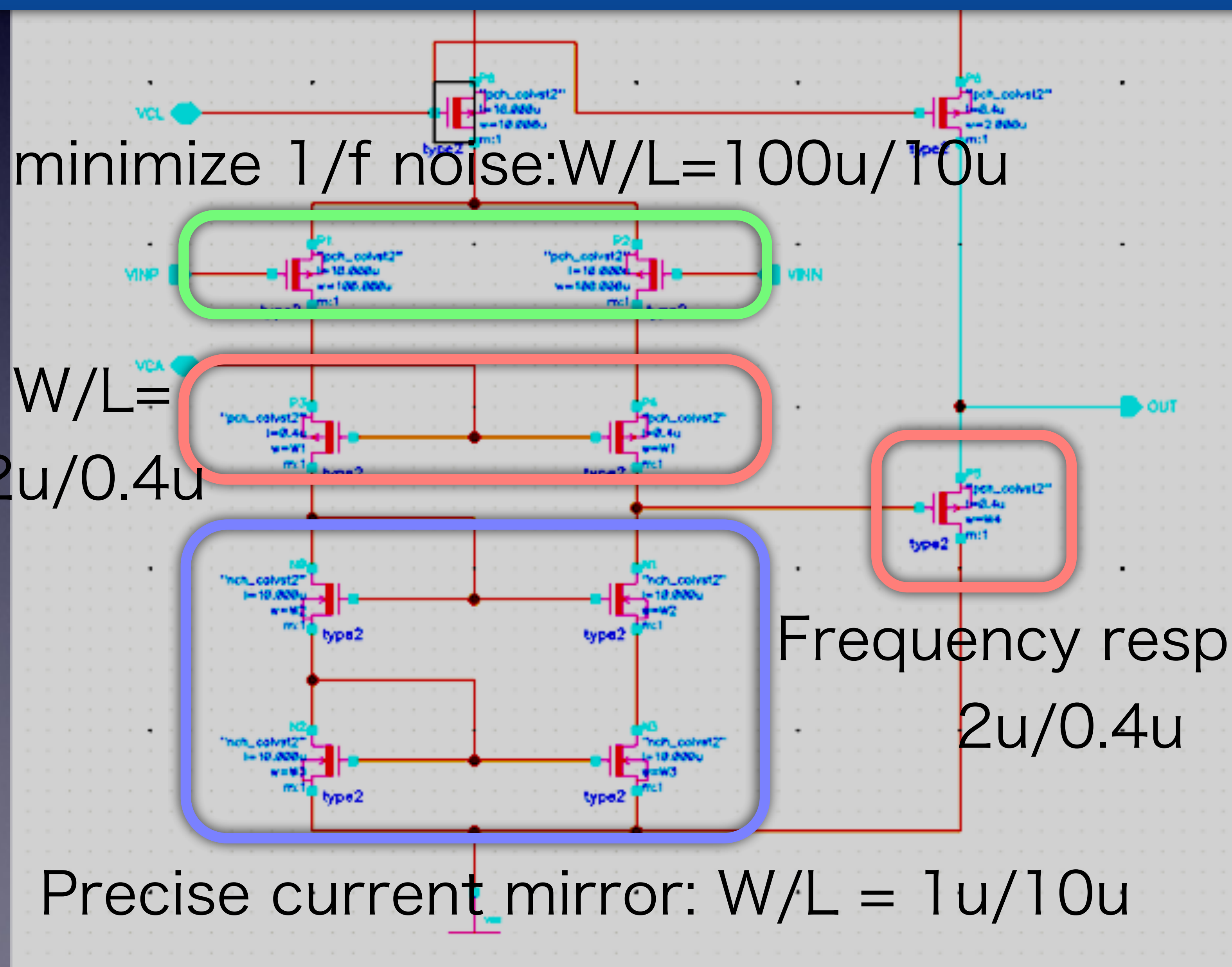
# Candidate of op-amp design

The telescopic cascode structure is employed
Low noise, low power dissipation and fast response



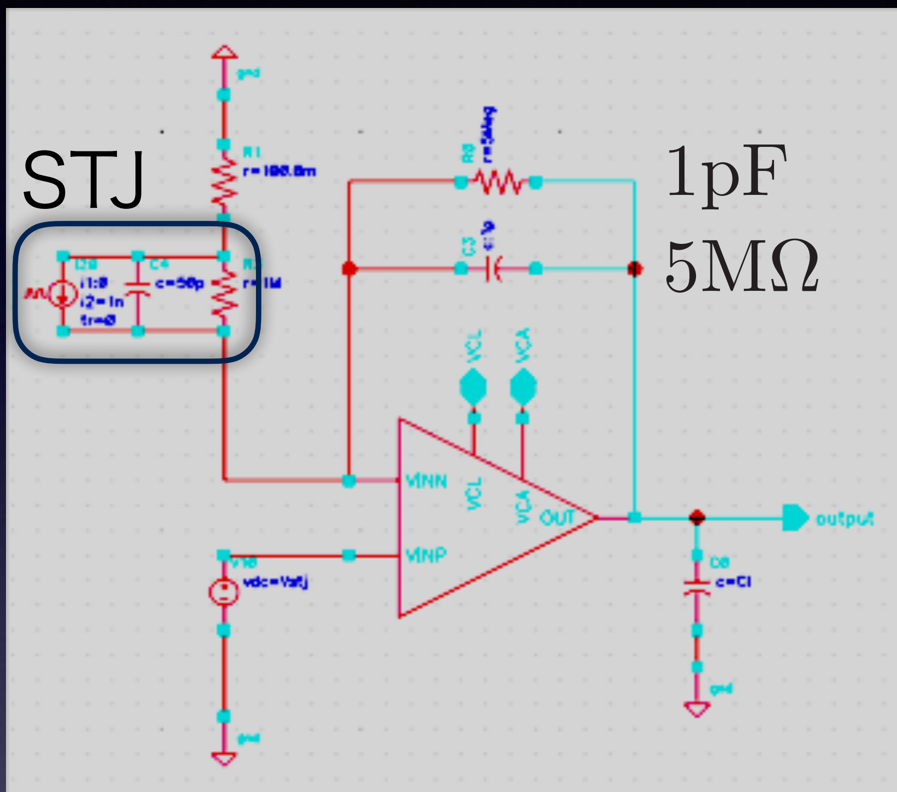

minimize 1/f noise:W/L=100u/10u

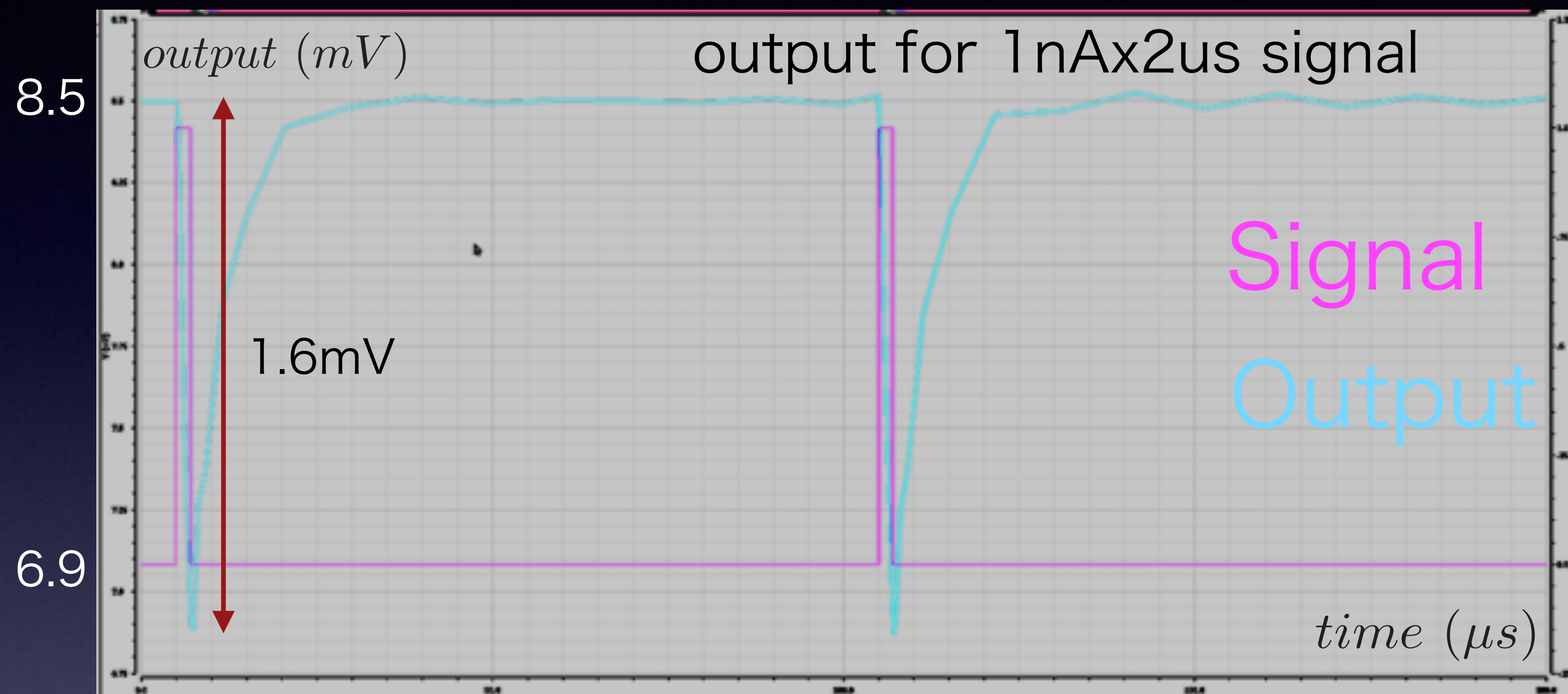
W/L= 2u/0.4u

Frequency response 2u/0.4u

Precise current mirror: W/L = 1u/10u

# Simulation result




- SPICE simulation(*) is performed with room temperature condition

  * Supported by VLSI Design and Education Center(VDEC), the U. Tokyo in collaboration with Synopsys, Inc., Cadence Design Systems, Inc., and Mentor Graphics, Inc.

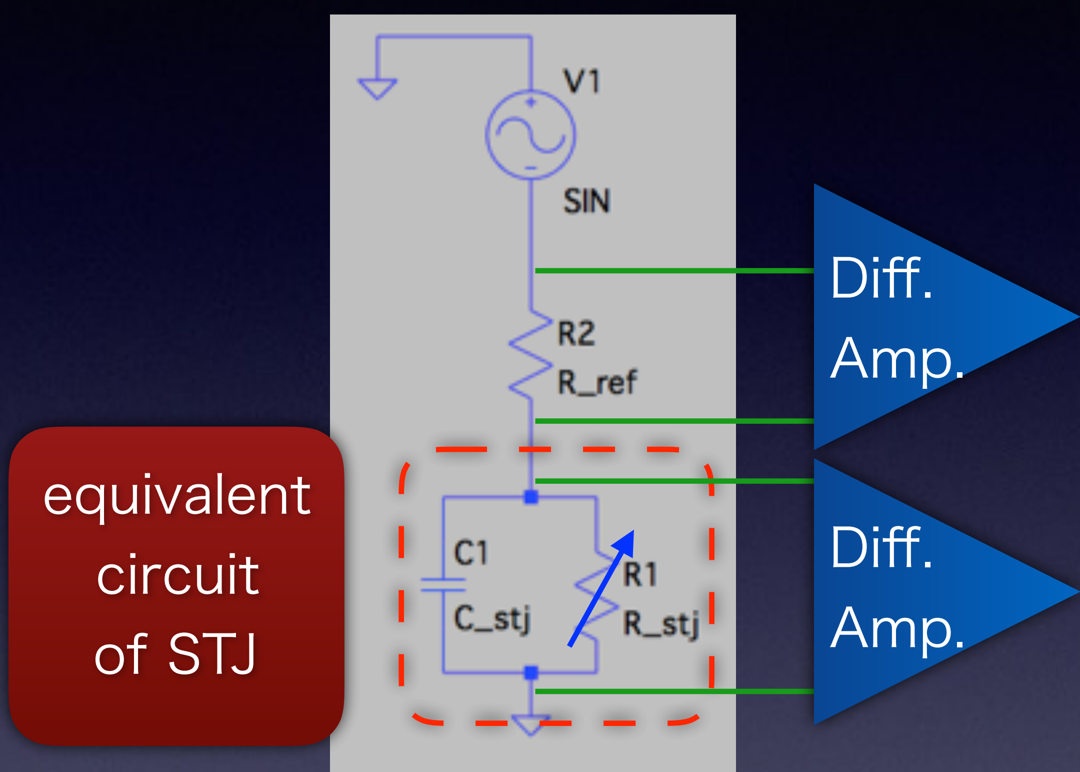
- Feedback capacitance and resistance are 1pF and $5\mathrm{M}\Omega$
- The assumed leakage current of STJ is 400pA@0.4mV
- The detector capacitance and load capacitance are 50pF
- 1nA x 2us = 2fC (600nm single photon) charge produces 1.6mV output

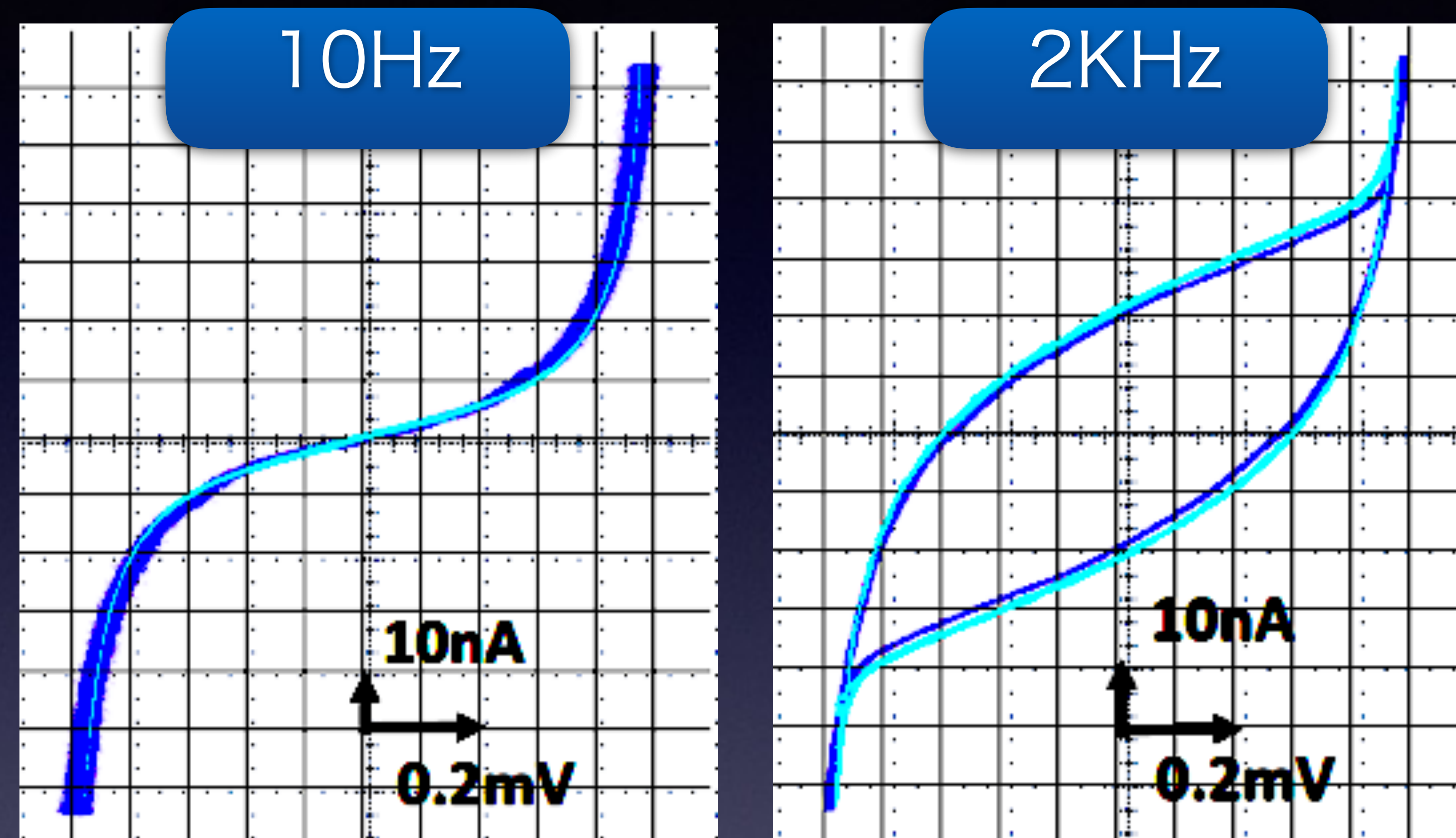
# Summary

- We are developing new spectrometer for single FIR photon
- The Nb/Al-STJ is well optimized for our experiment and shows leakage current of 250 pA $(50 \times 50 \mu m)$
- The IV characteristics of FD-SOI FETs are precisely measured at 3K
- The requirement for the cold amplifier is well estimated
- The design candidate of the cold amplifier shows good performance

# Capacitance of the STJ

IV measurement: 4-wire sensing




- The measured IV curve of STJ(Blue)@10Hz is reproduced using equivalent circuit(cap. + variable res.) in LTSpice(light blue)
- The measured IVs@500Hz and 2kHz are fitted by the simulated curves with various capacitance(0.1nF step)
- The capacitance of the best fit value is taken as the capacitance

$$I_{d_{sat}} = \frac{1}{2}\frac{W}{L}\mu C_{ox}(V_{gs} - V_t)^2 \rightarrow \frac{W}{L}\mu C_{ox} = 2(\frac{\partial\sqrt{I_{d_{sat}}}}{\partial V_{gs}})^2$$