Development of Superconducting Tunnel Junction Detector Using Hafnium for Neutrino Decay Search

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K.Takemasa[1], S.Kim[1], Y.Takeuchi[1], K.Kiuchi[1], K.Nagata[1], K.Kasahara[1], T.Okudaira[1], T.Ichimura[1], M.Kanamaru[1], R.Senzaki[1], K.Moriuchi[1], H.Ikeda[2], S.Matsuura[2], T.Wada[2], H.Ishino[3], A.Kibayashi[3], H.Sato[4], S.Mima[4], T.Yoshida[5], R.Hirose[5], Y.Kato[6], M.Hazumi[7], Y.Arai[7], E.Ramberg[8], J.Yoo[8], M.Kozlovsky[8], P.Rubinov[8], S.Kim[9]

[1]Univ. of Tsukuba, [2]JAXA/ISAS, [3]Okayama Univ., [4]RIKEN, [5]Univ. of Fukui, [6]Kinki Univ., [7]KEK, [8]Fermilab, [9]Seoul National Univ.

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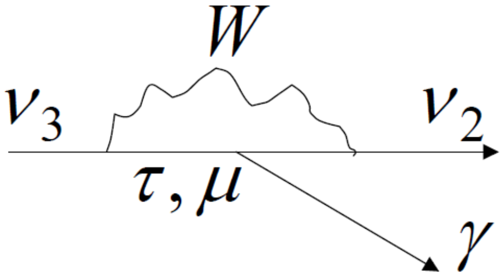
Motivation

- Difference between mass-squares of different generation neutrinos has been measured by various experiment of neutrino oscillation.
  - $\Delta m_{32}{}^2 = (2.32\ ^{+0.12}_{-0.08})\times 10^{-3}\ eV^2$, $\Delta m_{21}{}^2 = (7.50 \pm 0.20)\times 10^{-5}\ eV^2$
- However, neutrino mass itself has not been measured.
- Detection of neutrino radiative decay enables us to measure an independent quantity of the difference between squares of neutrino mass.
- → We can obtain neutrino mass itself from these two independent measurements.

Neutrino radiative decay

- Neutrino radiative decay is a radioactive decay in which a lighter neutrino and a photon are emitted from a heavier neutrino.
  - $\nu_3 \rightarrow \nu_2 + \gamma$
- Energy of the photon is given below
  - $E_\gamma = \frac{\Delta {m_{32}}^2}{m_3}$

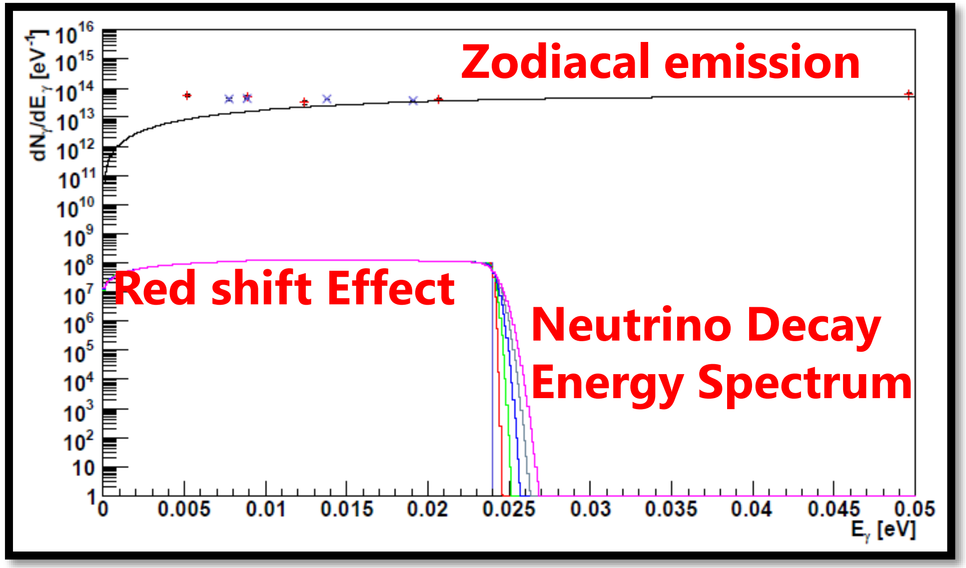


Feynman diagram of neutrino decay

- In the standard model, the heaviest neutrino lifetime is predicted to be 10^{43} years for ν_3 with a mass of 50 meV/c^2.
- In the left-right symmetric model, lifetime is calculated to be 1.5×10^{17}years

Neutrino radiative decay

- As neutrino lifetime is so long, to observe neutrino decay, we need an immense quantity of neutrino.
- Most promising method is to observe the decay of the cosmic background neutrino(CBN).
  - CBN has a temperature of 1.9K and a particle density ρ of 110 cm^{-3} per generation.



← Expected energy spectrum of CBN decay

and background (Zodiacal emission)

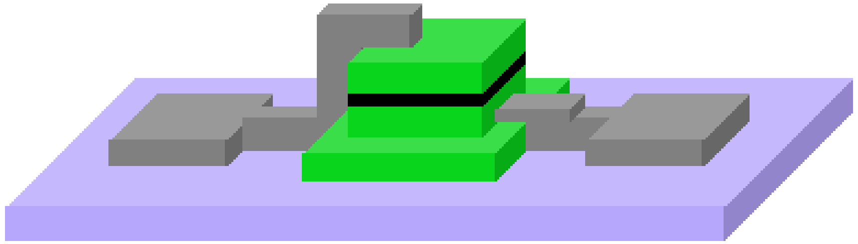
- m_3 = 50meV is assumed
- Eγ at neutrino rest frame = 25meV

- Energy spectrum of the photon from CBN decay has a cutoff at this energy and a low energy tail due to a red shift effect.

- Detector requirements from simulation
  - Continuous spectrum of photon energy around E_γ ~ 25meV (λ=50μm, far infrared photon)
  - Energy measurement for single photon with better than 2% resolution for E_γ ~ 25meV to identify the shape edge in the spectrum.
- → We adopted Hf–STJ as a detector for neutrino decay.

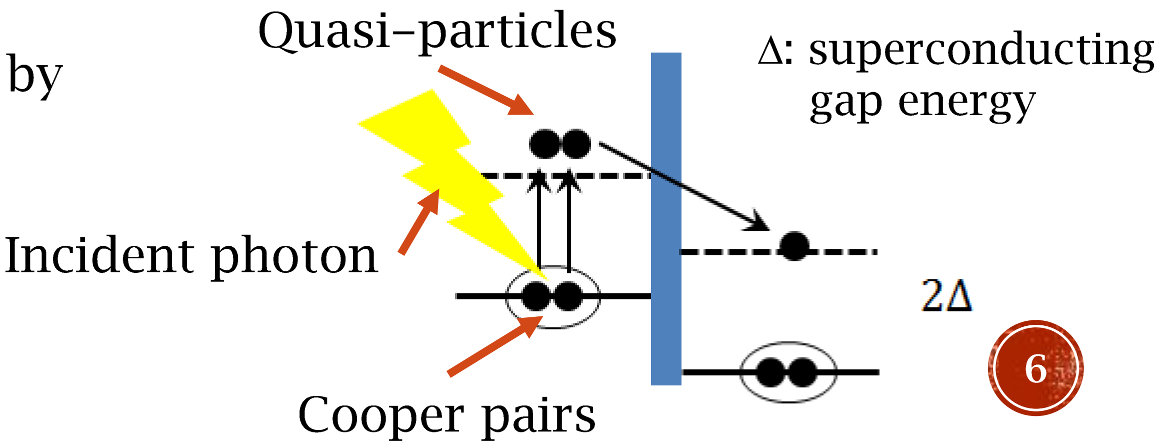
STJ (Superconducting Tunnel Junction) Detector

- **Structure**
  - STJ is a type of Josephson junction composed of Superconductor/Insulator/Superconductor
  - Size: dozens~hundreds μm square and 500 nm height



Overhead view of STJ detector

- **Working principle**
  - Incident photon is absorbed in the superconductor and excites cooper pairs.
  - Exited cooper pairs become quasi-particles.
  - Quasi-particles go through tunnel barrier by tunnel effect.
  - Number of quasi-particle is determined by energy of incident particle.
  - Thus, we can measure the energy of incident particle by measuring the tunnel current.



STJ energy resolution

- Statistical fluctuation in number of quasi-particles determines STJ energy resolution.
- Smaller superconducting gap energy Δ yields better energy resolution.

$$\sigma_E = \sqrt{(1.7\Delta)FE}$$

Δ: Superconducting gap energy
F: fano factor
E: Photon energy

Material	Tc(K)	Δ(meV)
Niobium	9.20	1.550
Aluminum	1.14	0.172
Hafnium	0.13	0.021

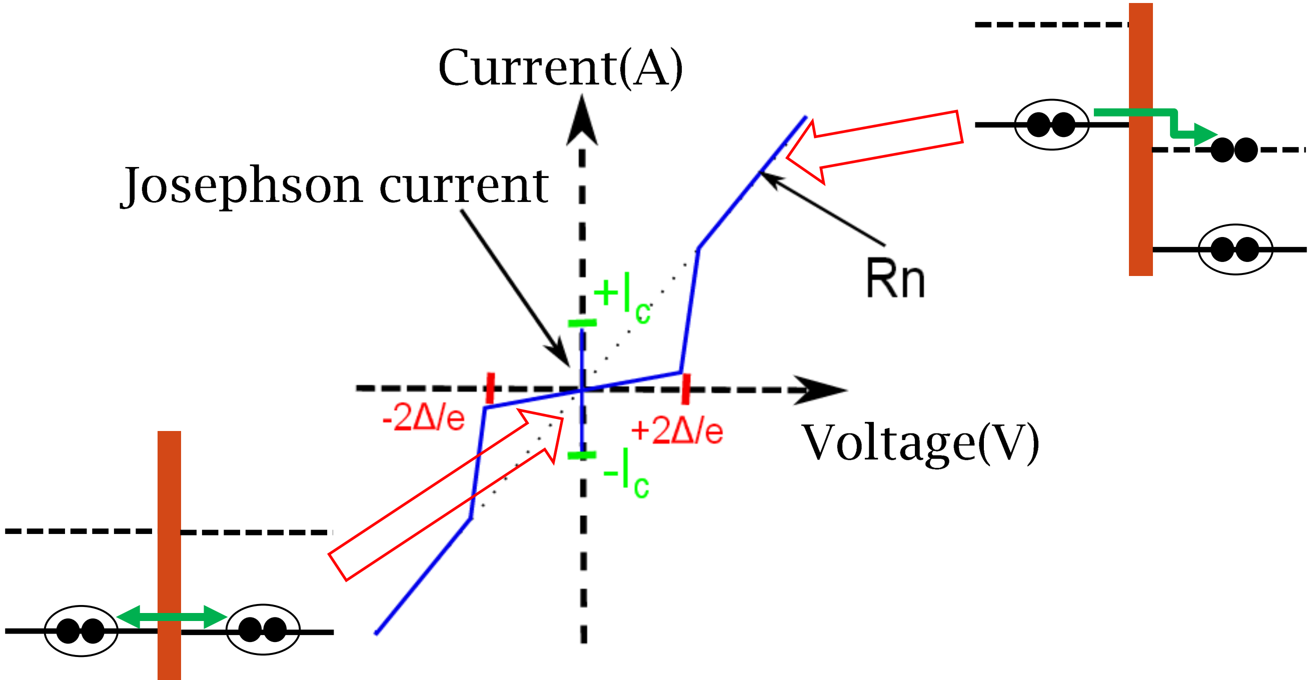
Tc : Superconducting critical temperature
Need ~1/10Tc for practical operation

- $N_{q.p.} = 25\text{meV}/1.7\Delta = 735$
- 2% energy resolution is achievable if fano factor <0.3

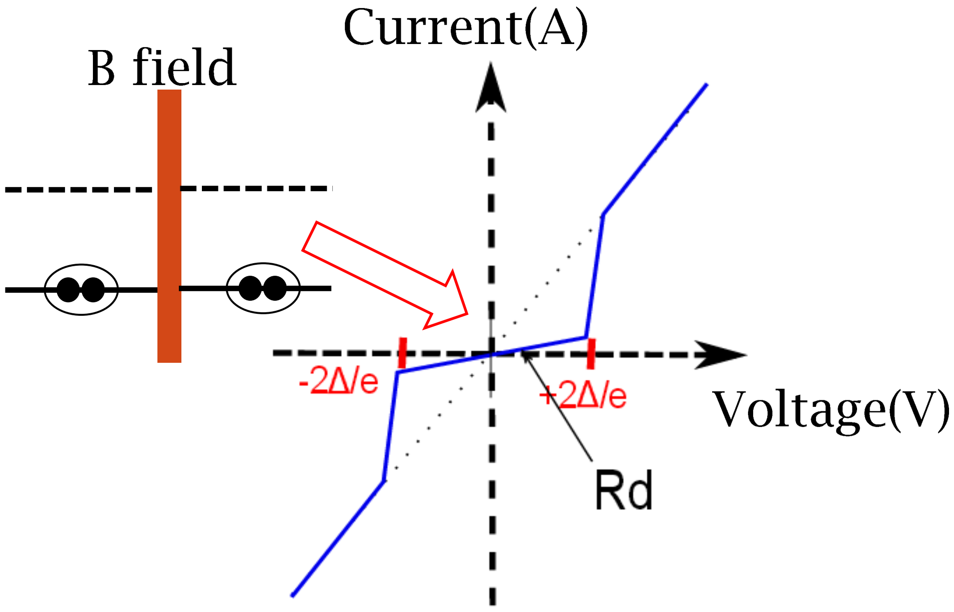
- Hf-STJ can generate enough statistics of quasi-particles from cooper pair breakings to achieve 2% energy resolution from photon with $E_\gamma = 25\text{meV}$.

IV curve of STJ detector

- The cooper pair tunneling current is seen at V=0, and the quasi-particle tunneling current is seen for $|V| > 2\Delta$.
- For detecting photons, STJ detector is operated with magnetic field of 10–100G.
- Josephson current is suppressed and change of quasi-particle tunnel current from incident particle can be measured.



Without magnetic field



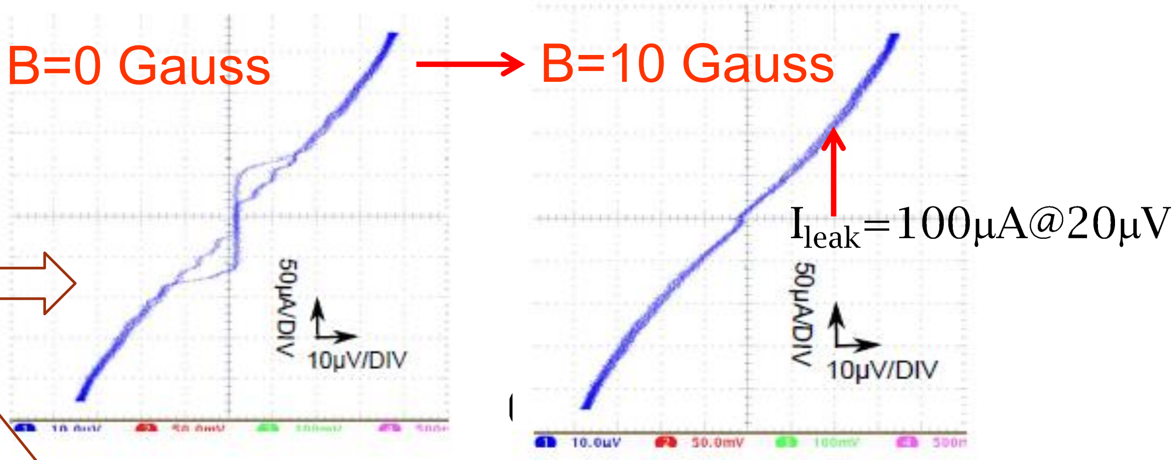
With magnetic field

Current status of development of Hf-STJ

- We succeeded in observation of Josephson current by Hf-HfOx-Hf barrier layer.
- However, as our Hf-STJ sample has large leakage current, optimization is underway.
- Downsizing
  - Hf-STJ(100×100μm²) shows smaller leakage current than Hf-STJ(200×200μm²).
- Also we are trying the following
  - Optimize condition for making the insulator.
  - Oxidation on side surface.

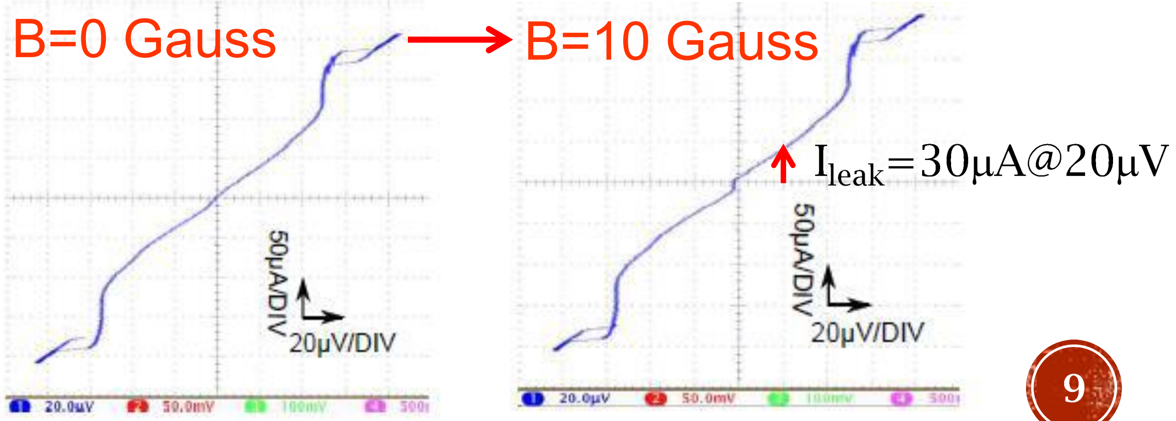
I-V curve of Hf-STJ (**200x200μm²**)

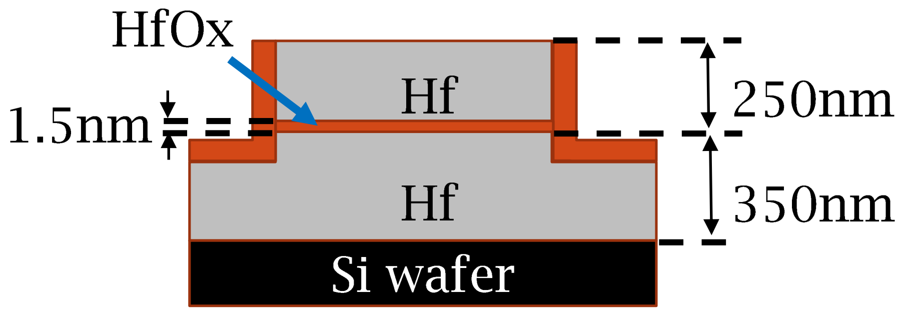
- T~80mK, I_c=60μA, **R_d=0.2Ω**



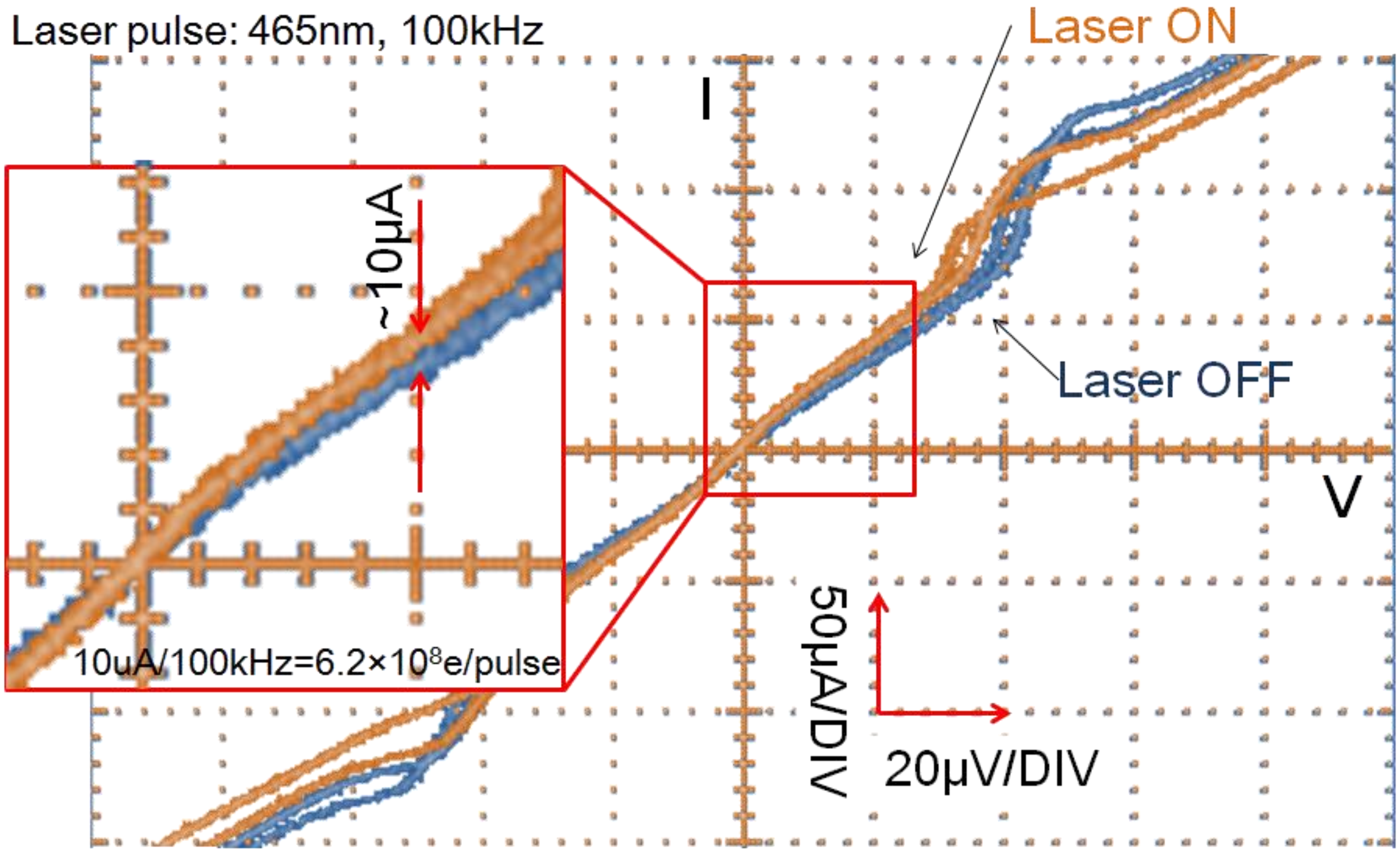
I-V curve of Hf-STJ (**100x100μm²**)

- T~40mK, I_c=10μA, **R_d=0.6Ω**



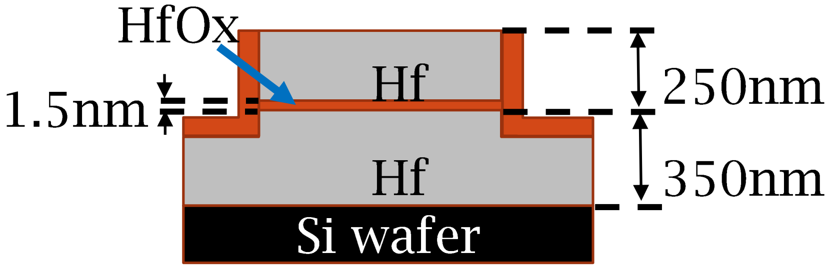


Response to DC light



We observed Hf-STJ response to visible light

- Sample information
  - 100×100μm²
  - R_d= 0.6Ω
  - T = 39~53mK



Summary

- We can determine neutrino mass if neutrino radiative decay is observed.
- To observe neutrino radiative decay, we are developing Hf-STJ detector.
- We succeeded in observation of Josephson current by Hf-HfOx-Hf barrier layer.
- Also, Hf-STJ response to the visible light was observed.
- However, our Hf-STJ sample has large leakage current of 30μA@20μV and need more improvement to function as a far-infrared photon detector.