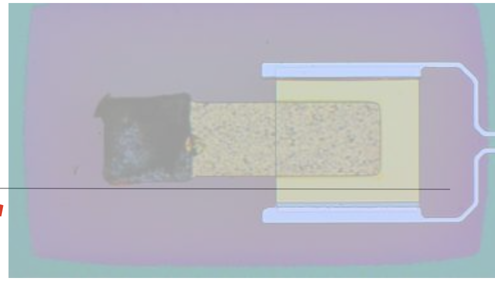
Dark Matter Symposium
29-30 March 2022 14:45-

B04-report



Development status of TES micro-calorimeters with 57Fe for solar axion search

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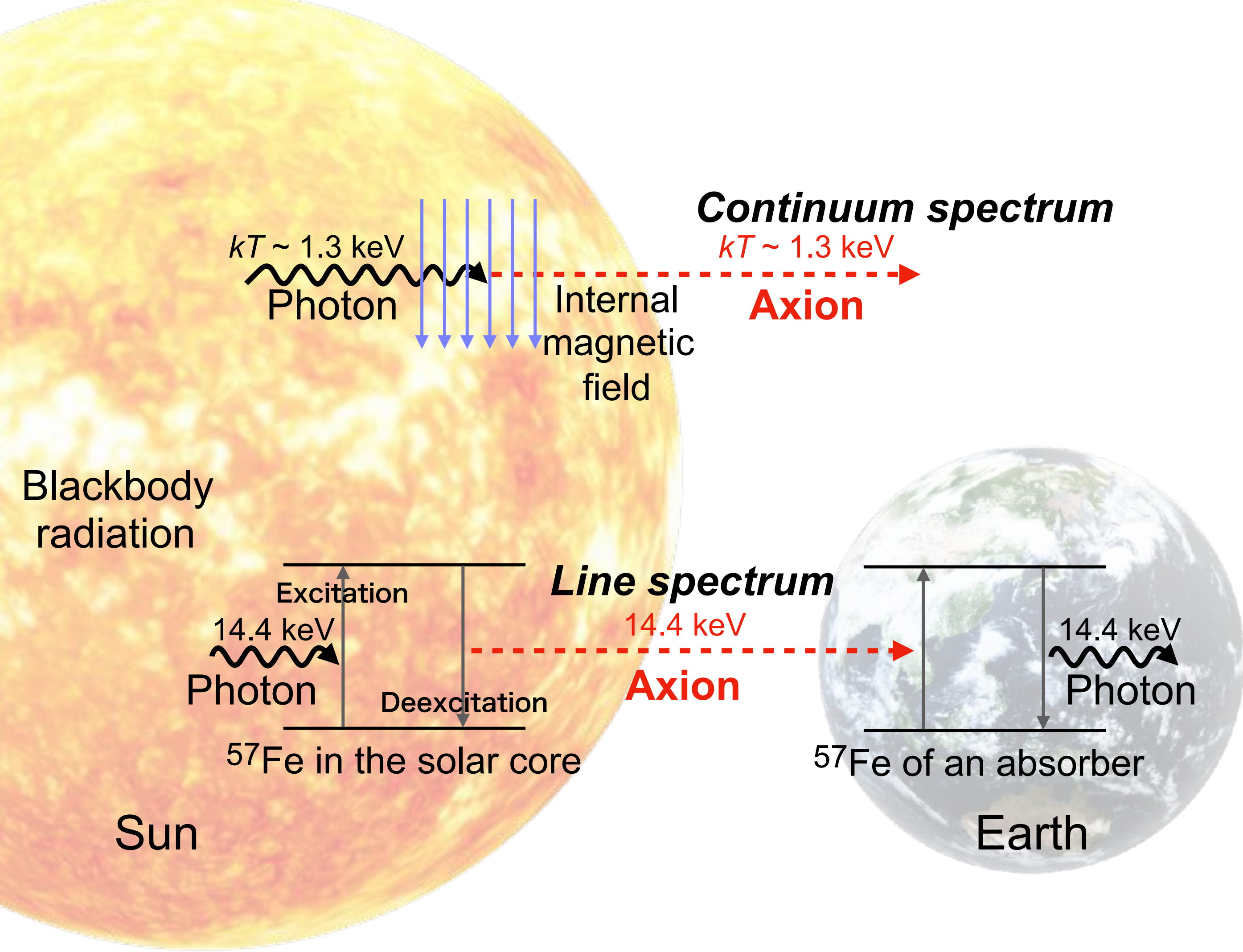
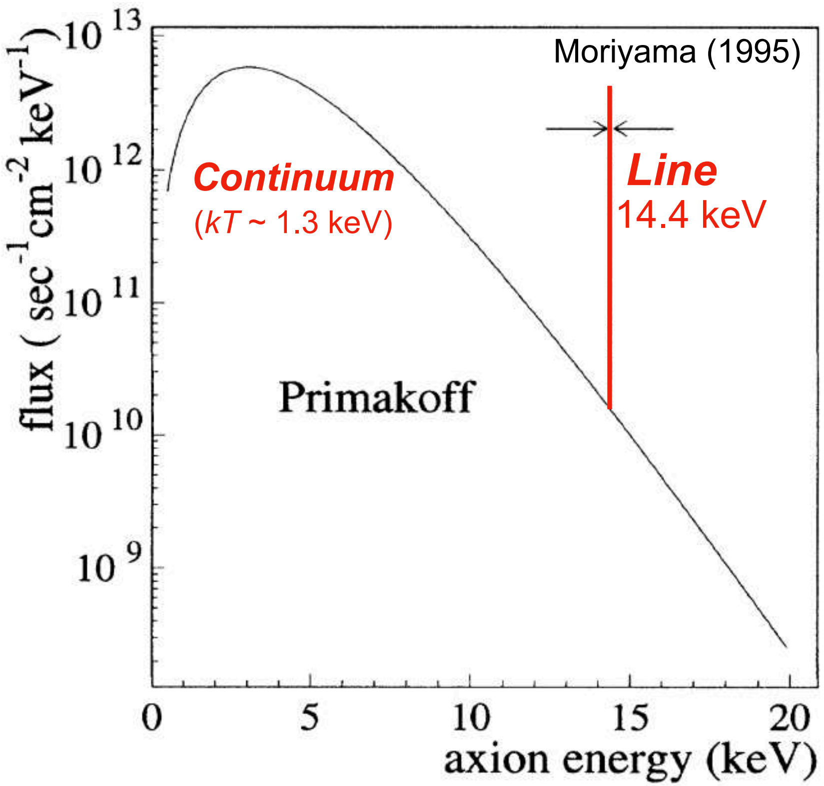
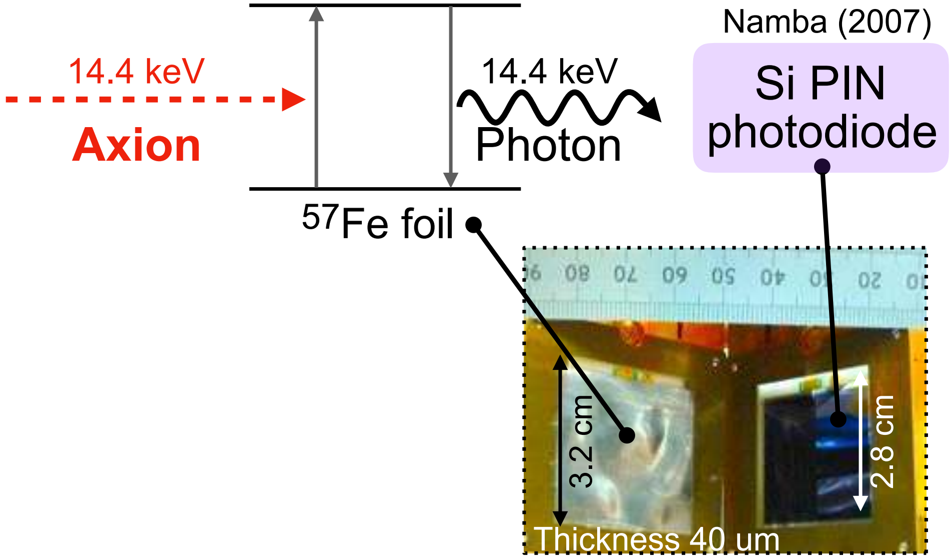
JAXA Japan Aerospace Exploration Agency
東京大学 THE UNIVERSITY OF TOKYO
北里大学 KITASATO UNIVERSITY
国立天文台 NAOJ National Astronomical Observatory of Japan
WASEDA University 早稲田大学
九州大学 KYUSHU UNIVERSITY

Expected Solar Axion Spectra





Mass Constraints Using Axion-Nucleon Coupling



- ✦ The branching ratio of 14.4-keV γ-rays — 10.5%
  That of conversion electrons and lower energy X-rays — 89.5%
- ✦ Self absorption by 35-um Iron foil — about 80%
- ✦ Solid angle of te detector — 86.6%
- ✦ Overall efficiency ~ 1%

Solar axion mass constraints using axion-nucleon coupling

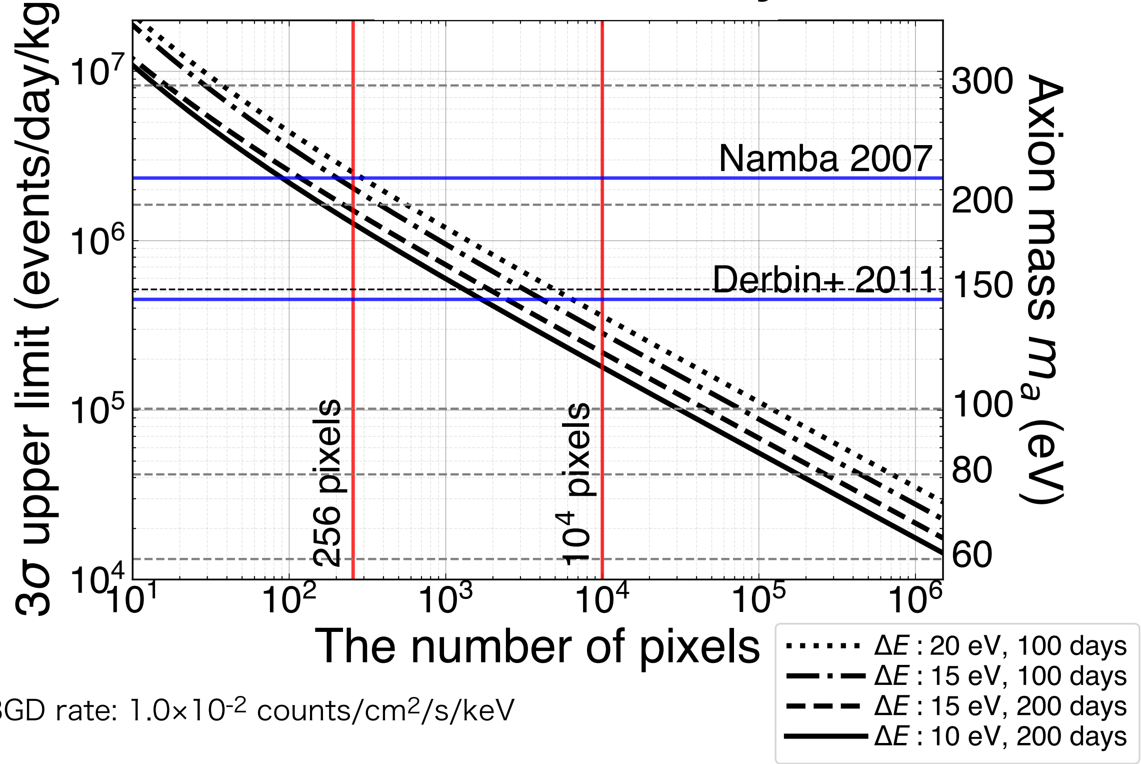
	Nucleon	Size	Mass	Time	Constraint
Namba 2007 **Si PIN photodiode**	^{57}Fe foil	35 um × 32 mm × 32 mm	211 mg	13.92 day	m_a ≦ 216 eV (95% C.L.)
Derbin+ 2011 **Si(Li) detector**	^{57}Fe foil	70 mm diameter, 30 mg/cm^2	1.26 g	44.8 day	m_a ≦ 145 eV (95% C.L.)
Gavrilyuk+ 2015 **Proportional gas chamber**	^{83}Kr gas	8.77 L	101 g	188.3 day	m_a ≦ 100 eV (95% C.L.)
Gavrilyuk+ 2018 **Proportional gas chamber**	^{83}Kr gas	8.77 L	58 g	613.25 day	m_a ≦ 12.7 eV (95% C.L.)

Using 57Fe as absorbers on transition edge sensor (TES) microcalorimeters
Much higher energy resolution dramatically improves the detection sensitivity

Detection Sensitivity

- ✦ TES calorimeters can detect self-absorbed thermal energy from axions
- ✦ Therefore, more than 70% of efficiency is expected
- ✦ Increase the converter mass by using an array device

The detection sensitivity of TES calorimeter array

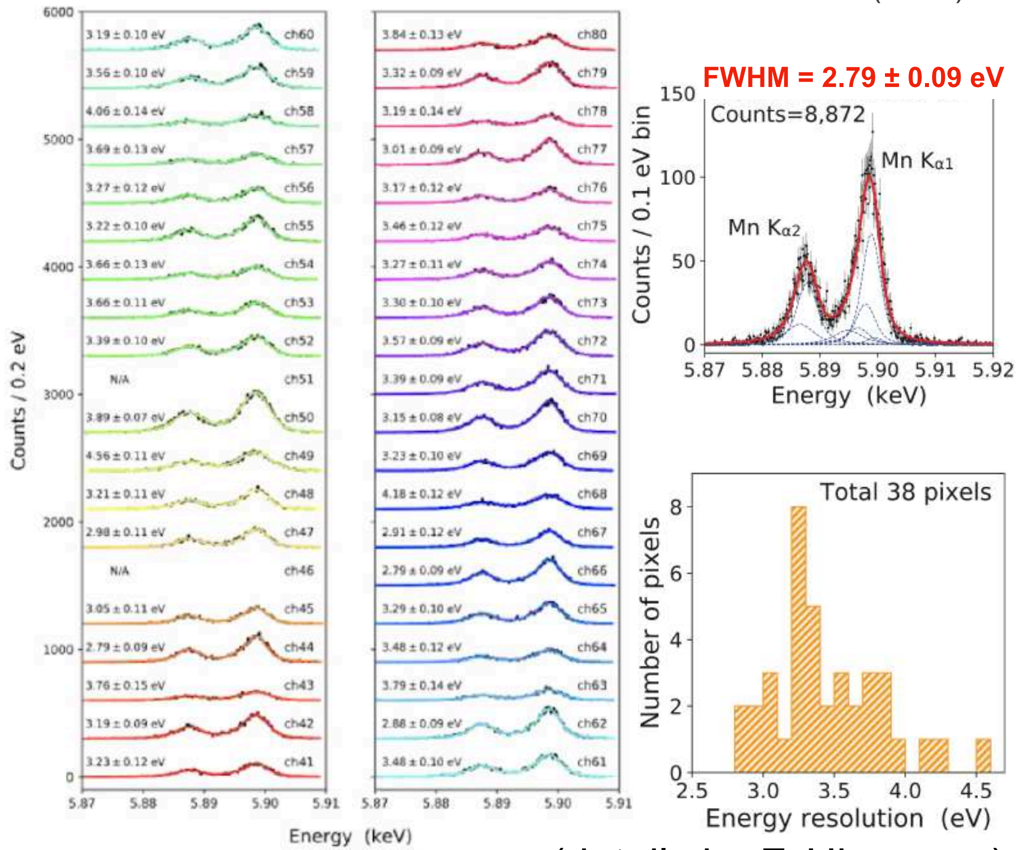


※ BGD rate: 1.0×10^{-2} counts/cm^2/s/keV

Low-noise microwave SQUID multiplexed readout

Spectra of total 38 channels

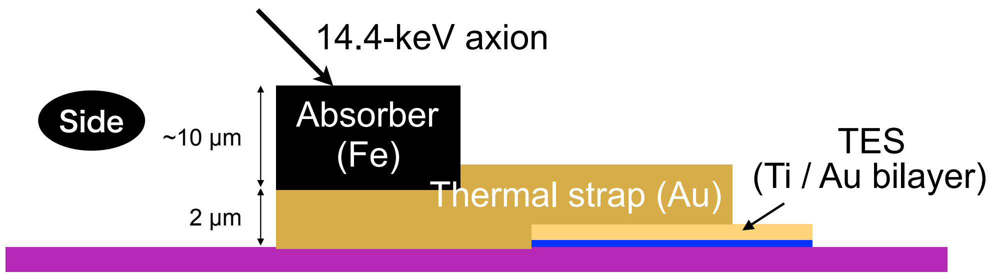
Nakashima+ (2020)



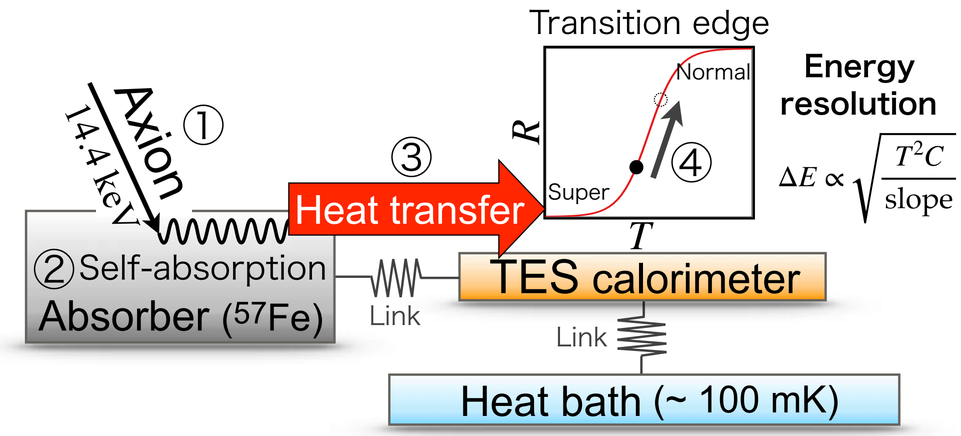
(details by F. Hirayama)

Requirements for Special Structure of TES Calorimeter

Special structure of TES microcalorimeter



Axion energy transfer in the calorimeter



Important points

✦ Special structure to keep high energy resolution (p.6)

✦ Iron absorber (p.7);
- ~ 10 um thickness
- good thermal conductivity

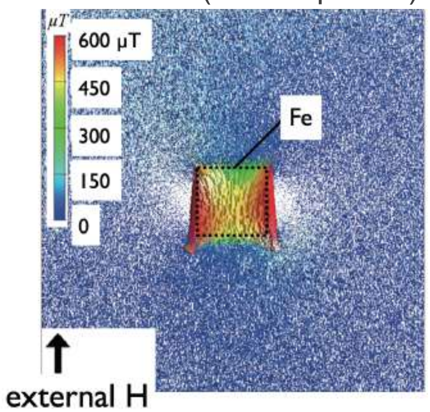
✦ Gold thermal strap (p.10);
- good thermal conductivity

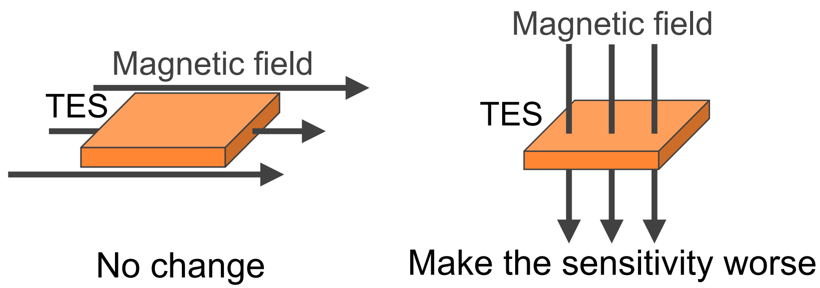
✦ Reproducibility of TES (pp.11-13);
- New evaporative deposition inst. by Henkaku funding

Optimization of Microcalorimeter's Structure

The spectroscopic performance of a TES could degrade under a magnetic field made by ferromagnetic iron absorbers

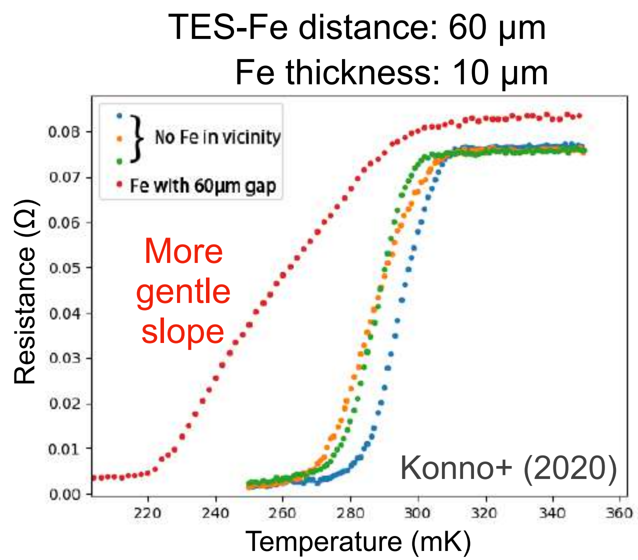
Maehisa+ (LTD17 poster)



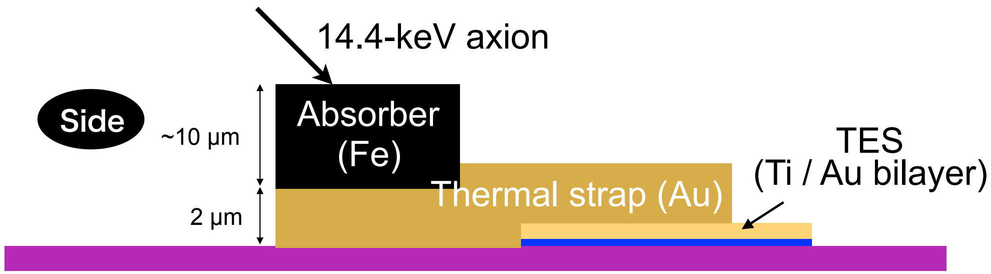


Our magnetic simulations

Fe - TES minimum distance is 30 μm for an iron of 5 μm thickness



To place the absorber at a certain distance from the TES and to connect them with a thermal strap



Energy resolution

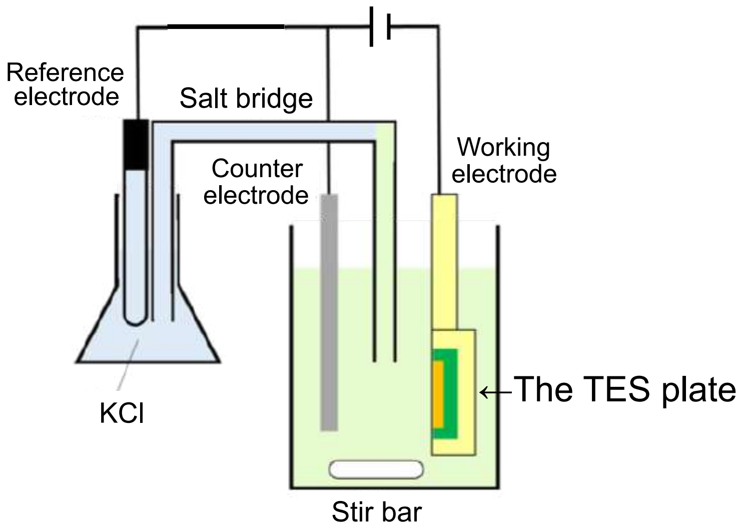
$$\Delta E \propto \sqrt{\frac{1}{\text{Slope}}}$$

Need to fabricate a test device and confirm the performance (p.8)

Electrodeposition for Iron Absorbers

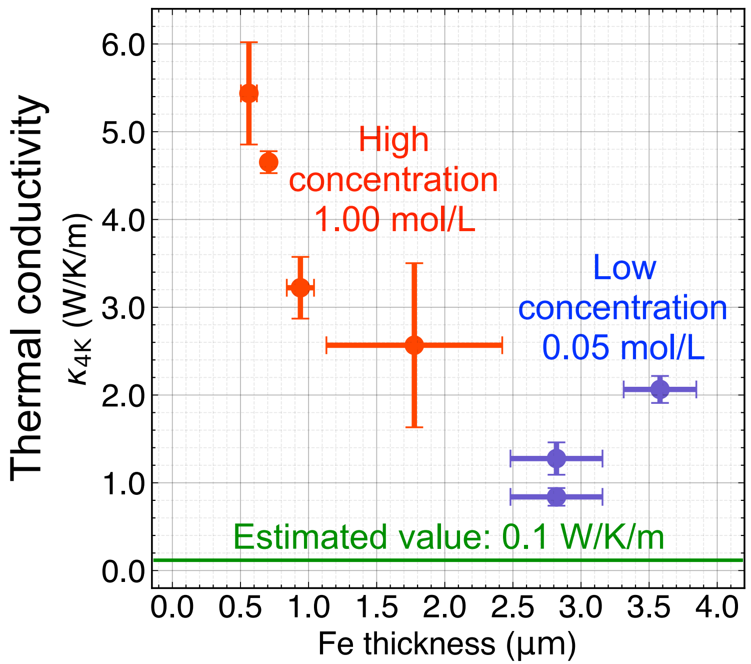
- ✦ Thick iron absorber with good thermal conductivity is required
- ✦ Electrodeposition is suitable to make thick structure, but electroplating of pure iron is not established
- ✦ Collaboration with experts in Waseda Univ.

Electrodeposition



Metal deposition : $Fe^{2+} + 2e^{-} \rightarrow Fe$

Competitive reaction : $2H^{+} + 2e^{-} \rightarrow H_2 \uparrow$



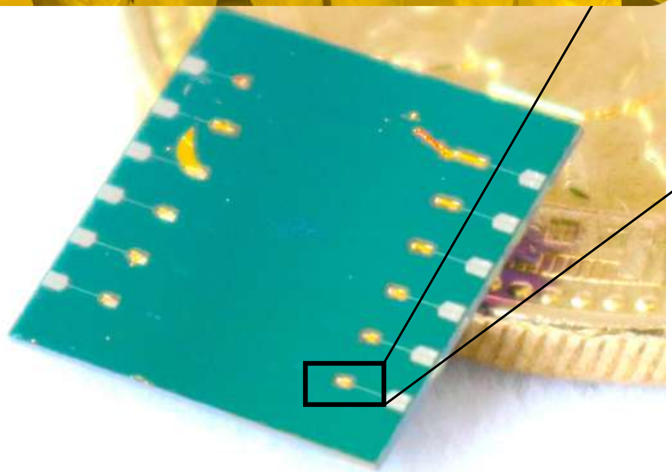
Achieved more than ten times higher thermal conductivity than expected value even in low concentration

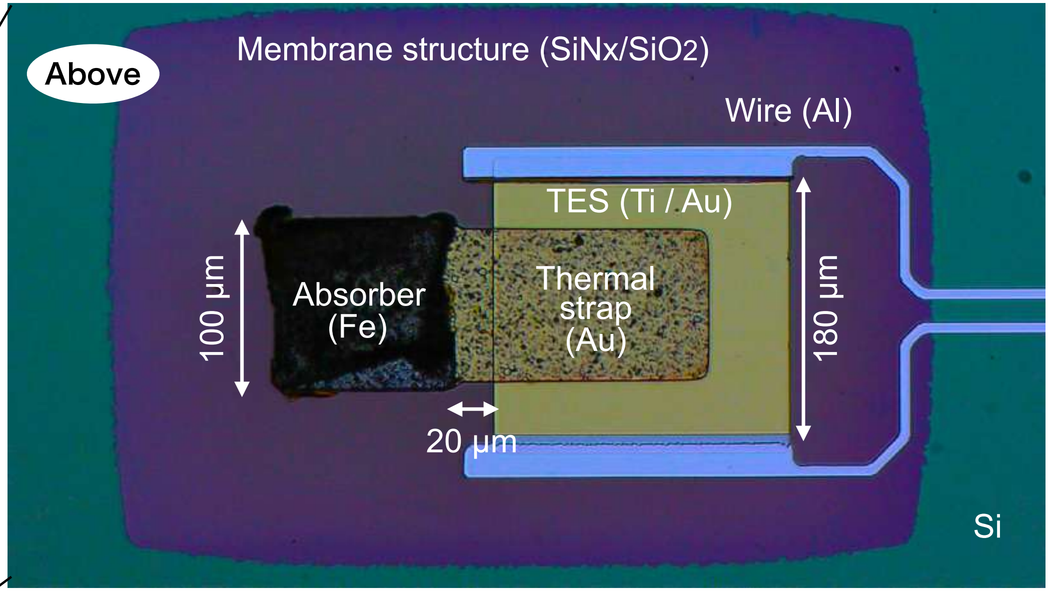
Still on the way

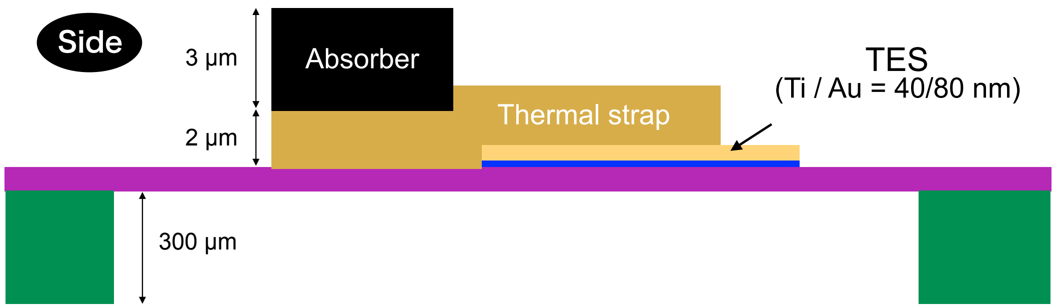
- ✦ Aimed improving yield rate
- ✦ 10 um of target thickness
- ✦ Still setting conditions close to production environment

Fabrication of Dedicated TES with Iron Absorber

Nanoelectronics clean room
at ISAS/JAXA

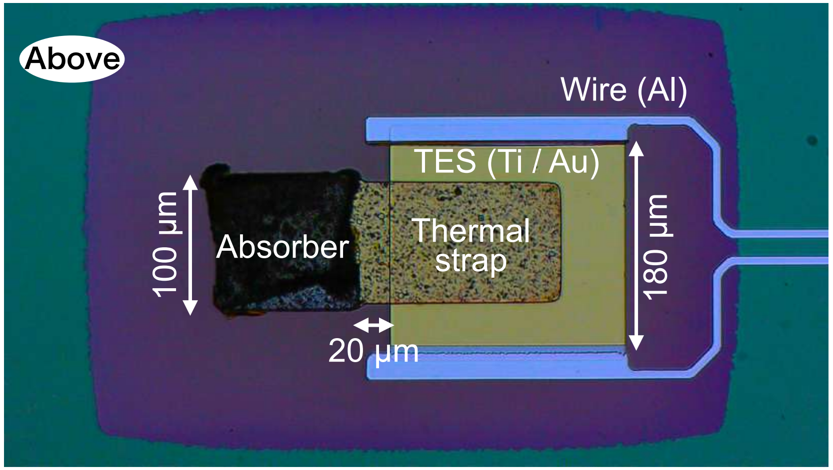






16/24 elements were successfully produced

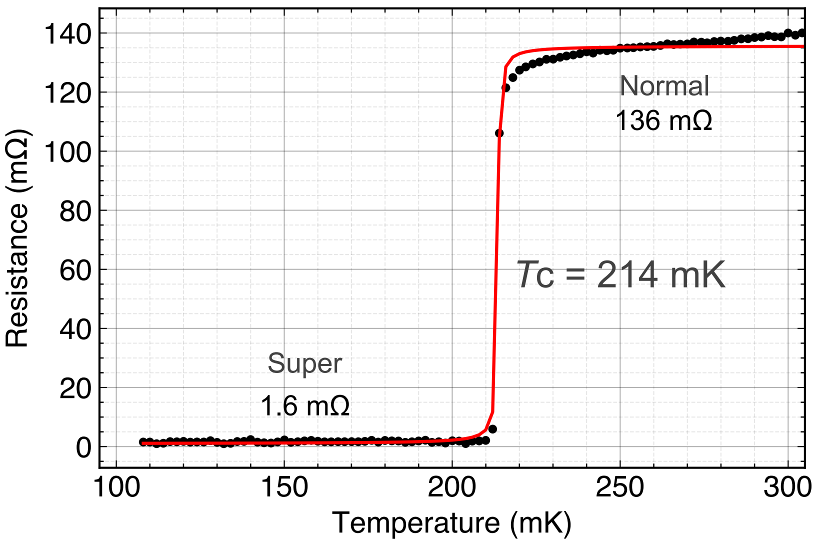
X-Ray Irradiation Test on Single Pixel TES



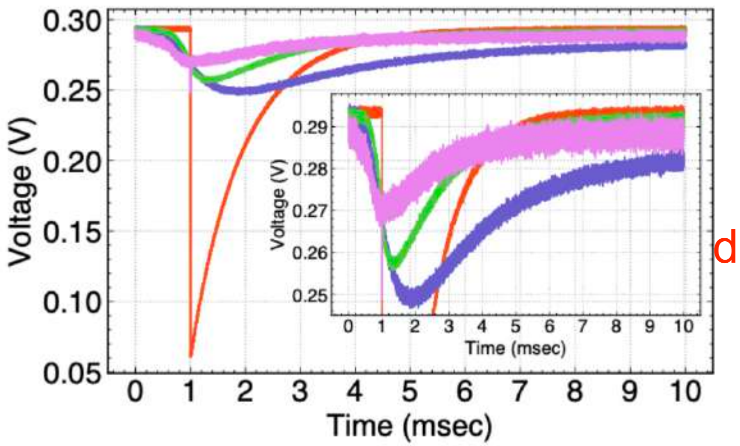
We successfully operated the TES microcalorimeter with a distance between TES and absorber under iron magnetization for the first time

- ✦ ^{55}Fe radiation source; 5.9 keV, 6.4 keV lines
- ✦ Obtained 698 pulses by SQUID readout

R-T curve by the four terminal method



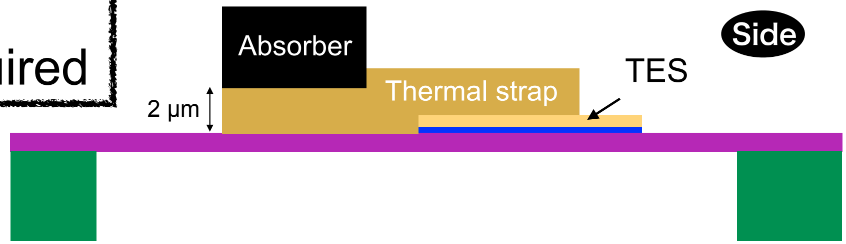
Obtained signals in an irradiation test



To decide each event position, we have worked on more detailed and accurate simulations with Kyushu Univ.

Improved Thermal Conductivity of Thermal Straps

To achieve high energy resolution in this structure,
the high thermal conductivities of thermal gold straps are required

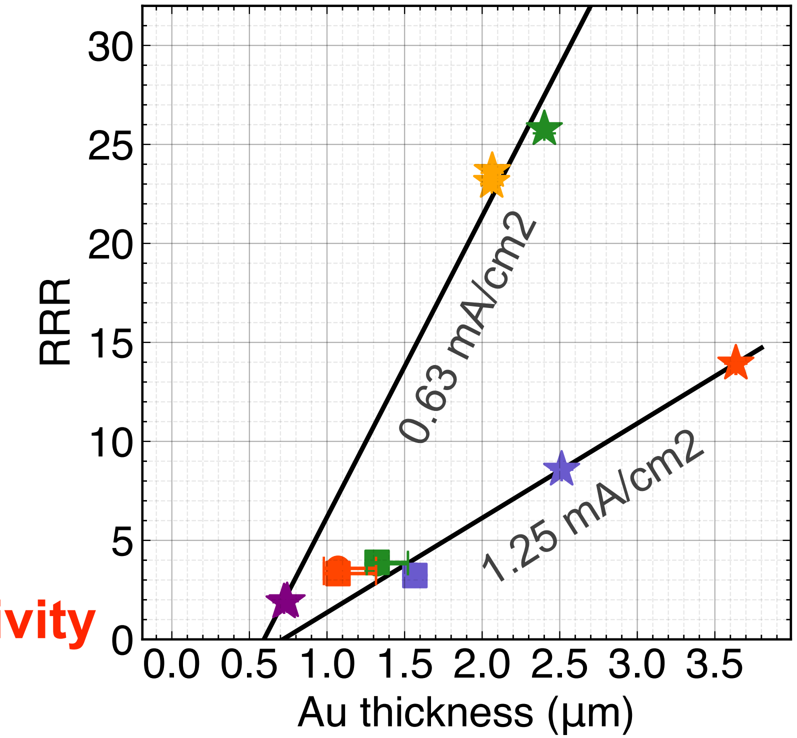


The residual resistivity ratio (RRR): the indicator of the thermal conductivity

$$\mathrm{RRR}_{300\mathrm{K}/4\mathrm{K}} = \frac{\rho_{300\mathrm{K}}}{\rho_{4\mathrm{K}}}$$

High RRR→ High thermal conductivity

2020		2021
Evaporative deposition	→	Electro-deposition
RRR ~ 2.8		RRR > 23



Achieved more than eight times higher thermal conductivity than previous straps deposited evaporative

Introduced Evaporative Deposition Instrument for TES

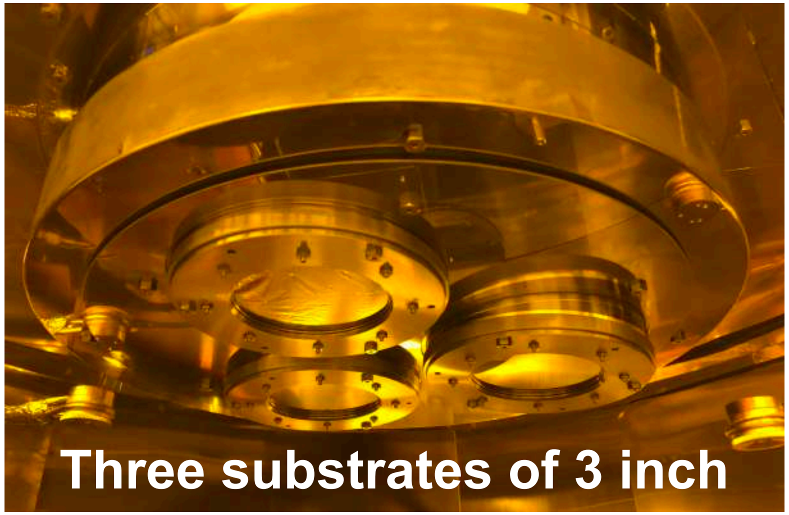
Sputtering (-2020)

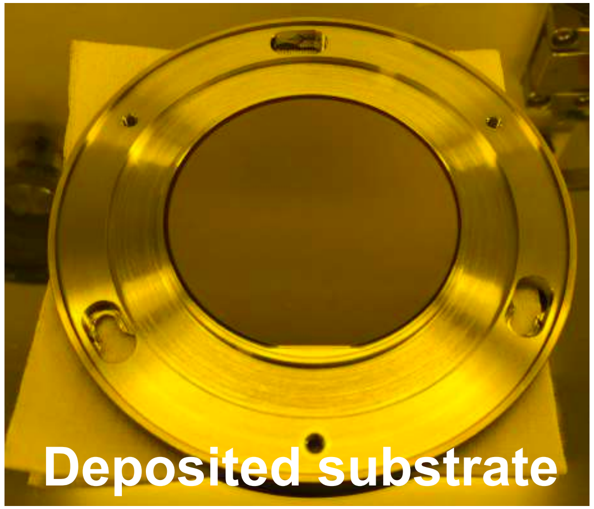
- ✦ Non-reproducibility of Tc
- ✦ Only one substrate of 2 inch in one deposition

Evaporative (2021- , by Henkaku funding)

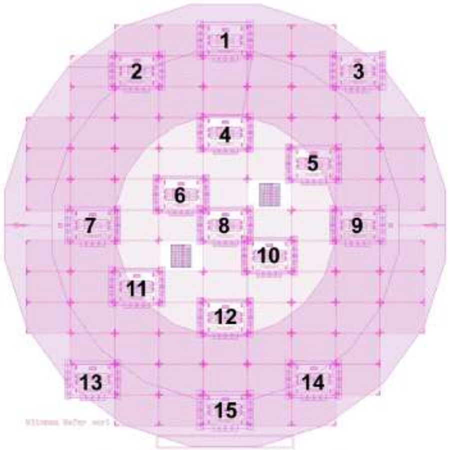
- ✦ Introduced evaporative deposition instrument in 2021 spring
- ✦ Automatic control of thickness and time
- ✦ Three substrates of 3 inch in one deposition


Evaporative deposition inst.

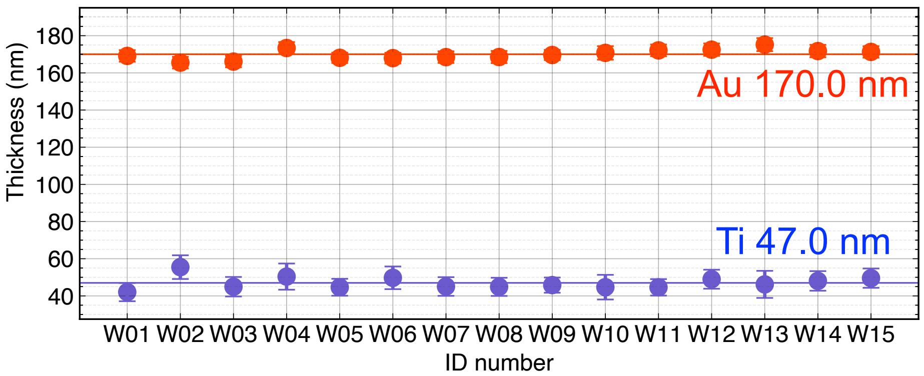

Three substrates of 3 inch


Deposited substrate

Thickness Distribution and Tc Control

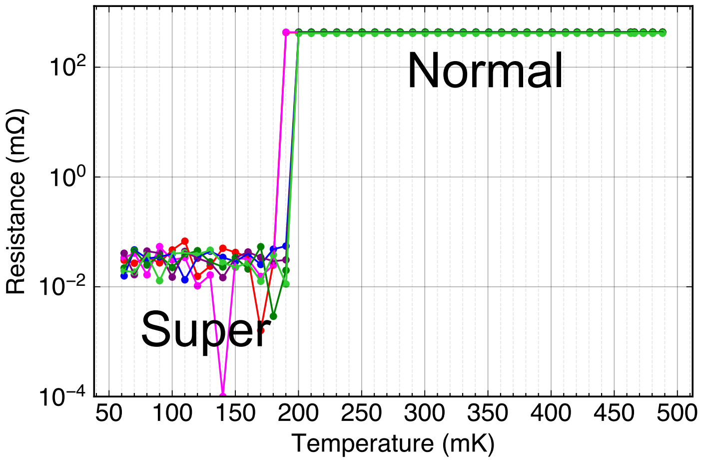


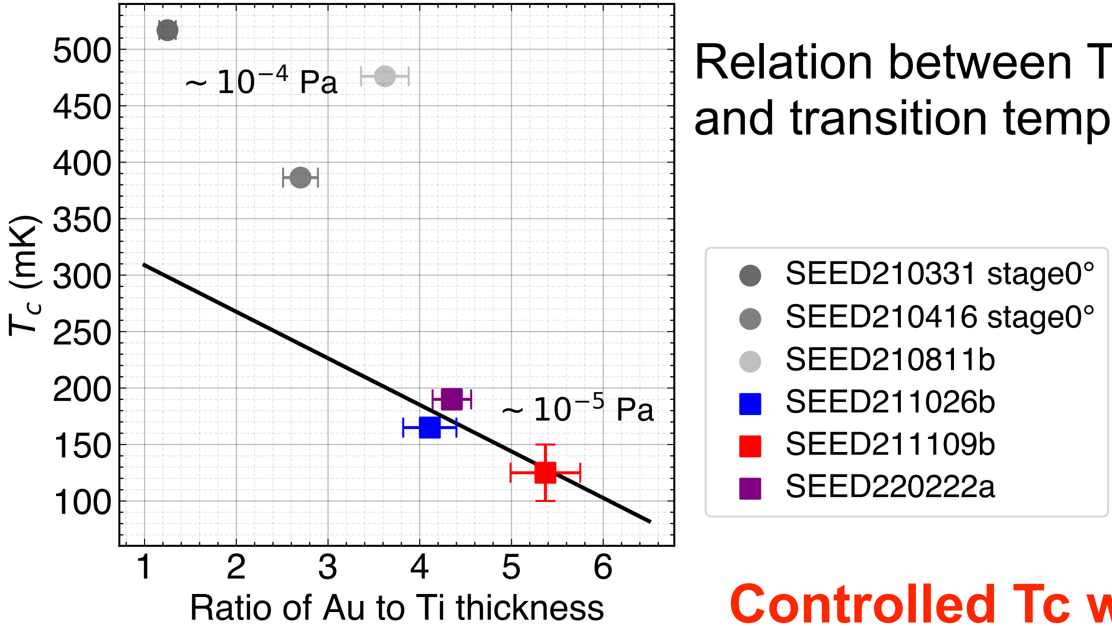
TES (Ti/Au) thickness distribution



Confirmed TES-flatness in 3-inch substrate

Transition edge

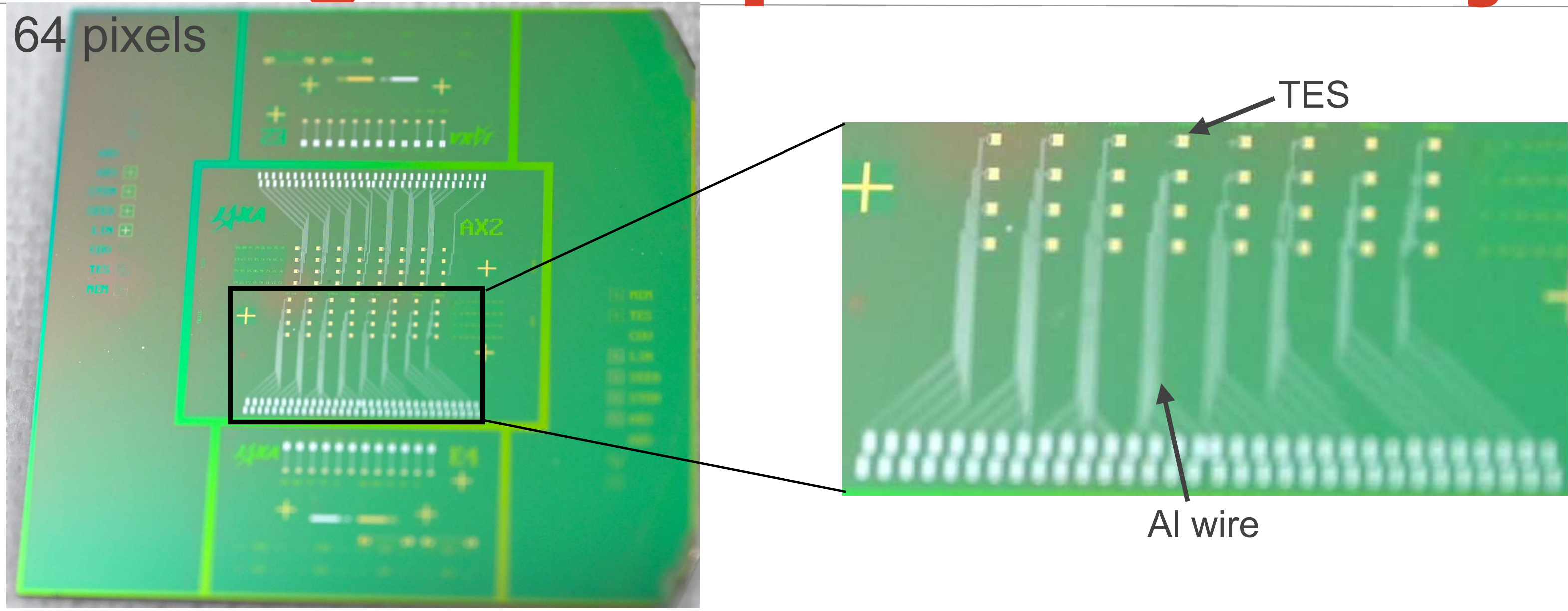




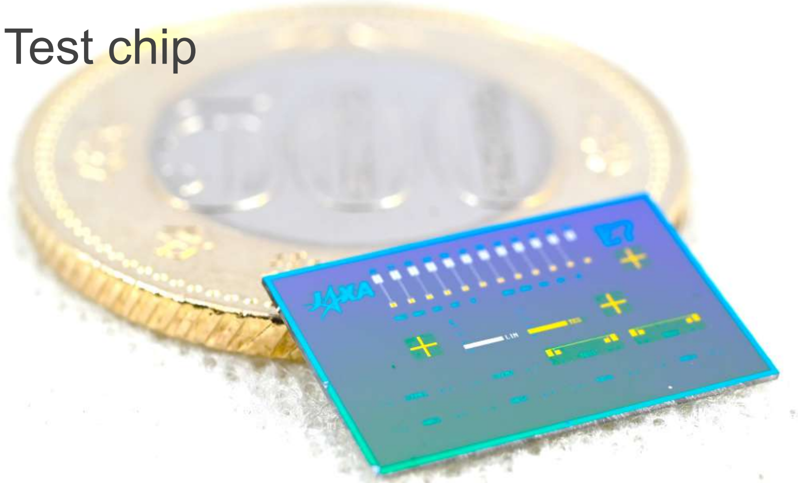
Relation between Ti/Au ratio and transition temp.

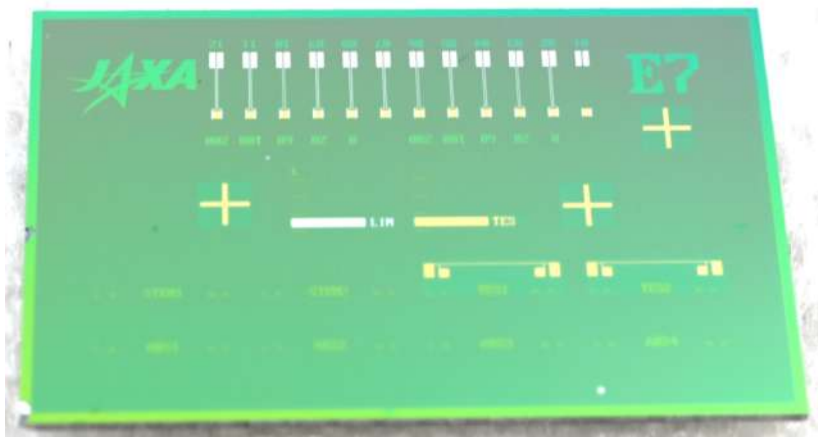
Controlled Tc with Ti/Au ratio

Designed 64-pixel TES array



Test chip





Summary and Next Steps

Summary

★Develop high-efficiency TES microcalorimeters for 14.4-keV solar axion search

★Special structure to avoid the degradation of transition sharpness under iron magnetization

★Successfully operated the TES with a distance between TES and absorber for the first time

★Try setting conditions for Iron absorbers

★Achieved electro-deposition of high thermal conductivities for gold thermal straps

★Be possible to fabricate TES efficiently having high reproducibility

Next steps

★To measure in details the effect of transition sharpness under iron magnetization

★To perform evaluation a few pixels of 64 pixels under 14.4-keV radiation source