Superconductor tunnel junction (STJ) soft X-ray detector for SR

+ Superconductor Strip Photon Detector (SSPD)

IFDEPS2018

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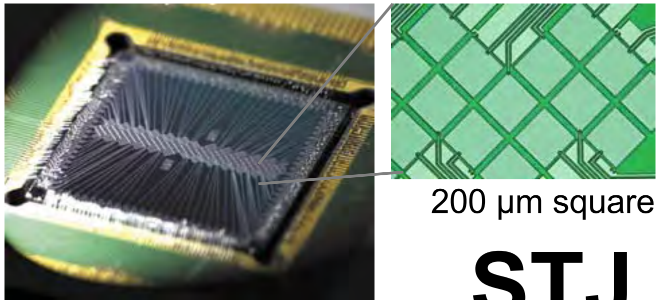
National Institute of Advanced Industrial Science and Technology (AIST)

Yu-Shan Huang, Te-Hui Lee, Di-Jing Huang

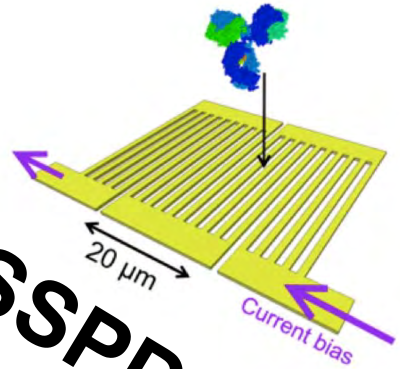
National Synchrotron Radiation Research Center



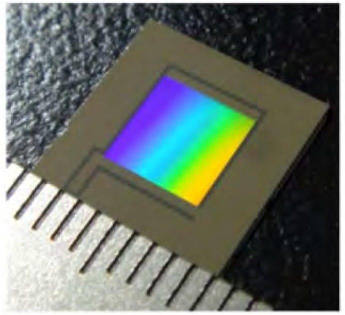
200 μm square

Nb/Al

STJ

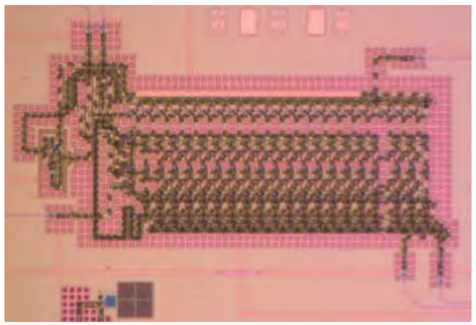


SSPD



Nb, NbN, MgB_2

NICT, CNR - Institute SPIN



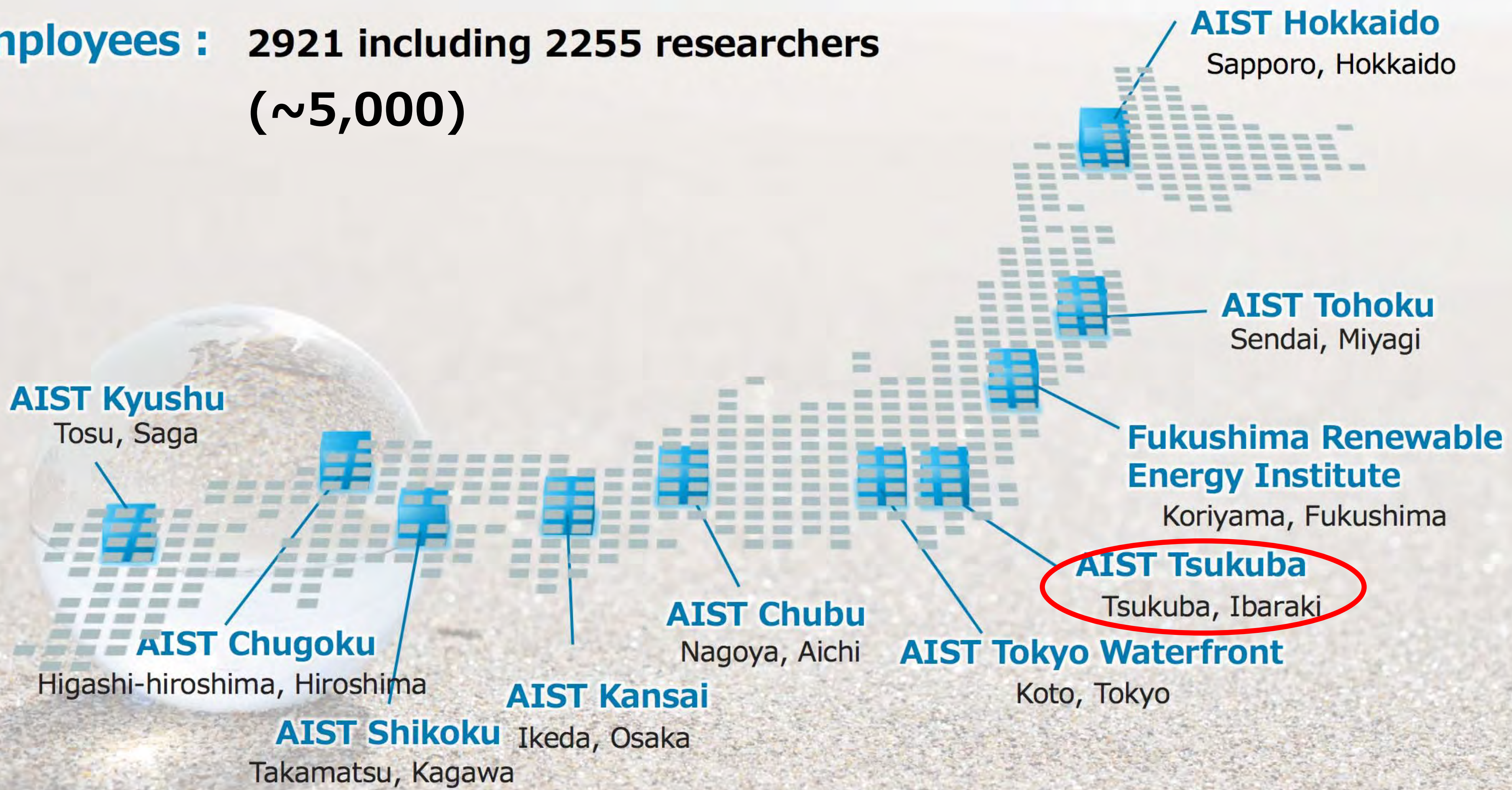
SFQ-TDC Time-to-digital converter for TOF-MS (Yokohama National Uni.)

AIST campuses

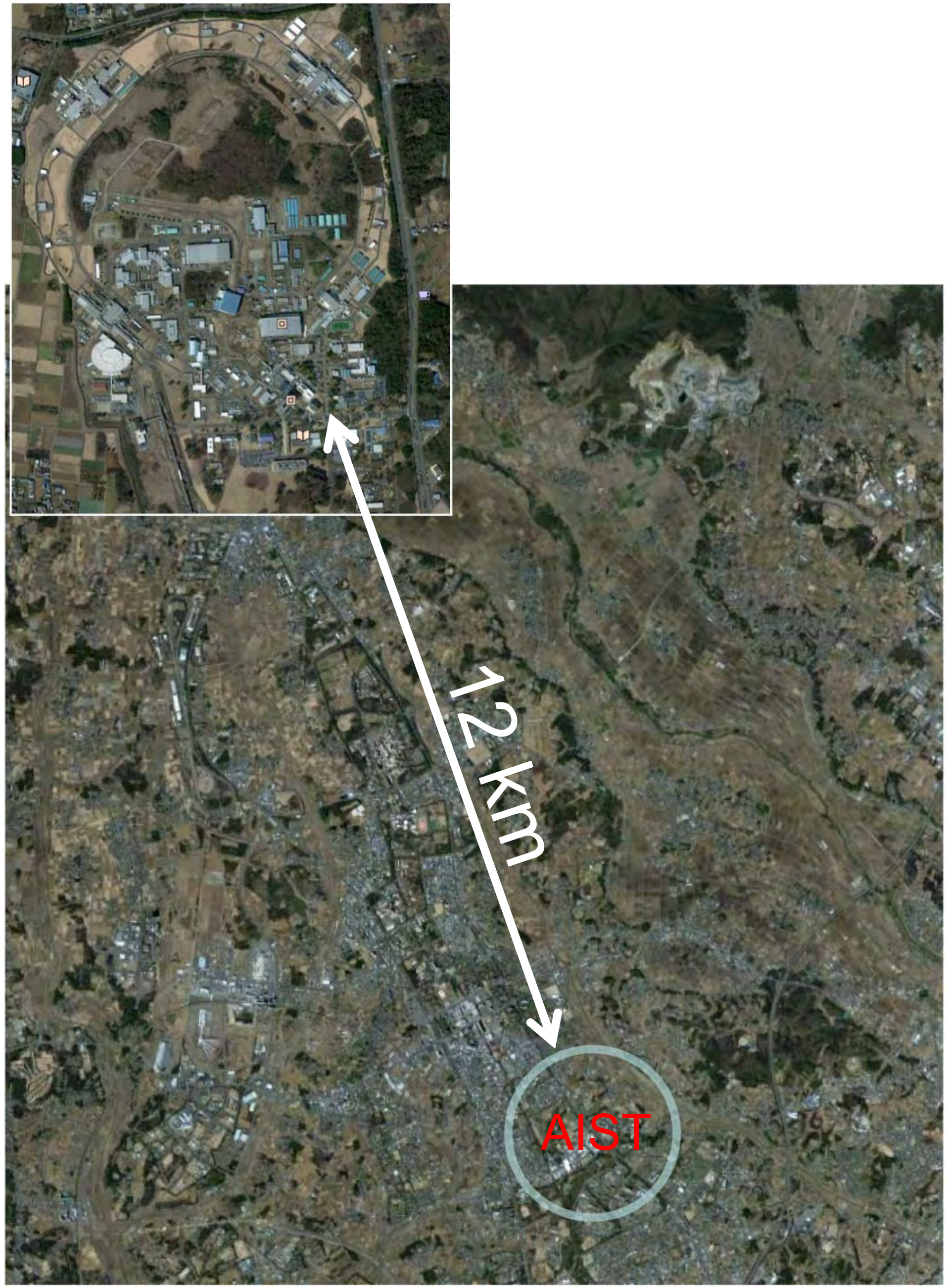
National Institute of Advanced Industrial Science and Technology AIST

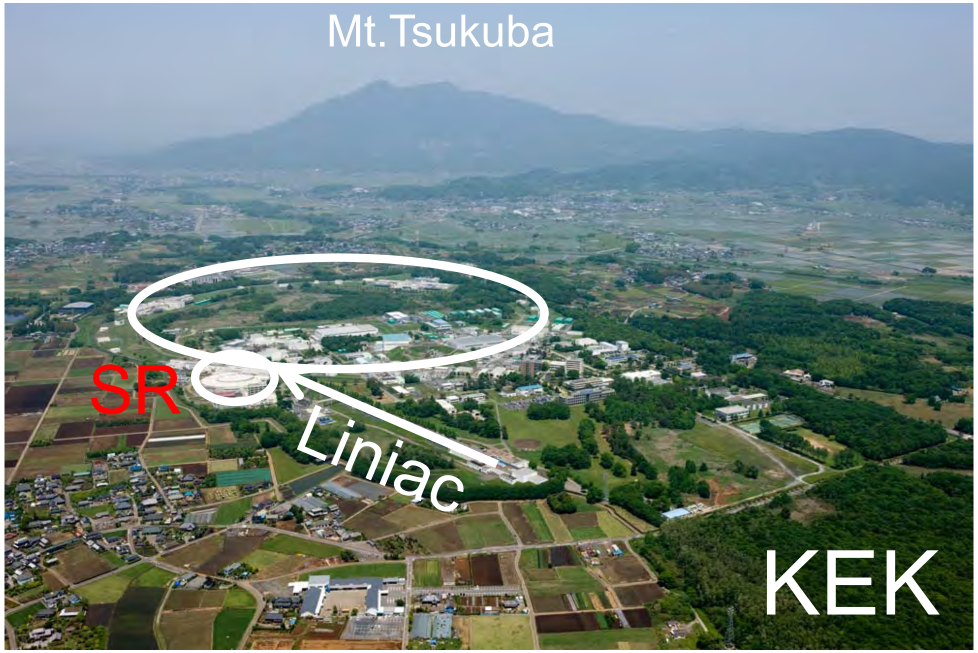
Employees : **2921 including 2255 researchers**

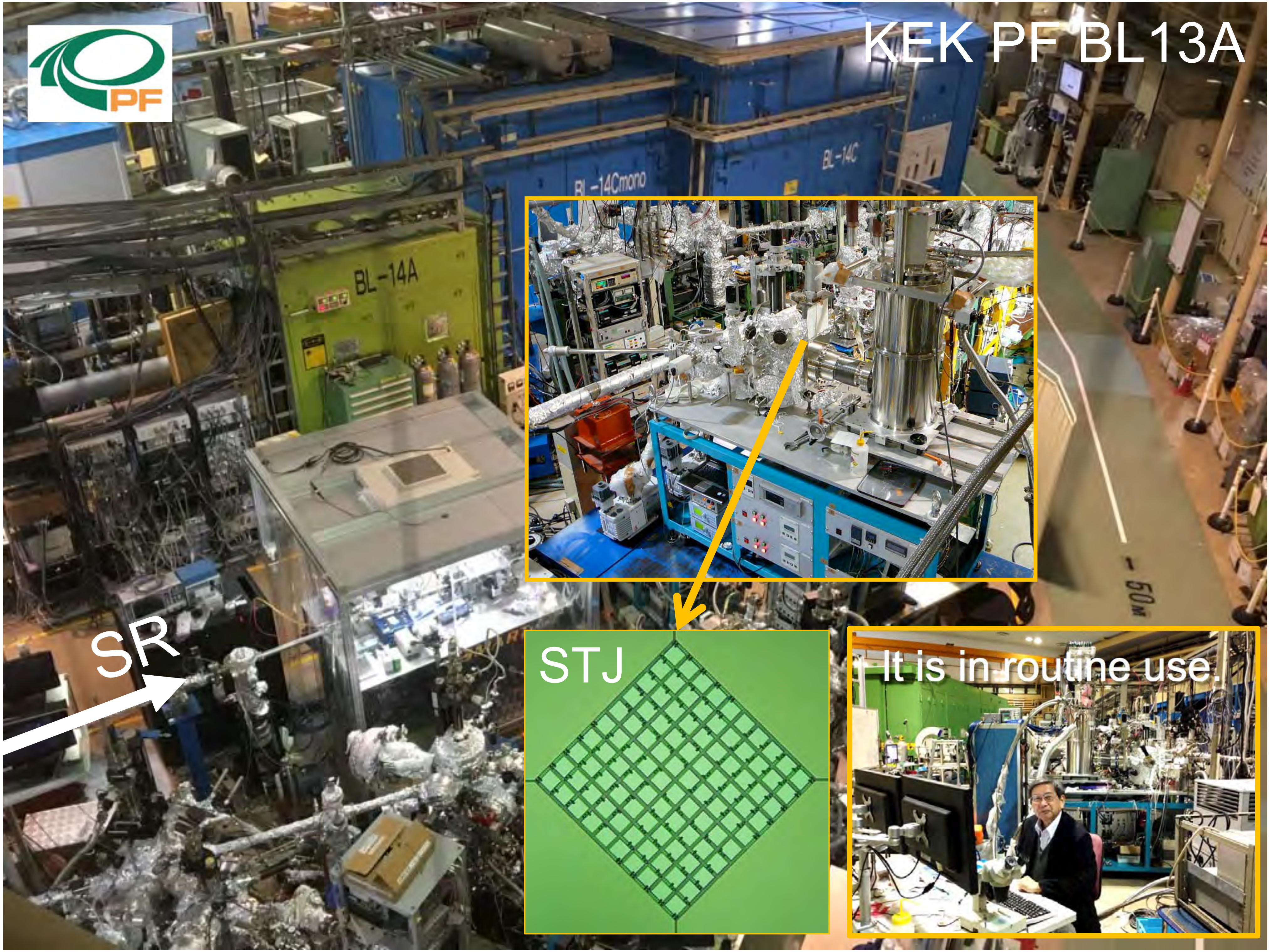
(~5,000)



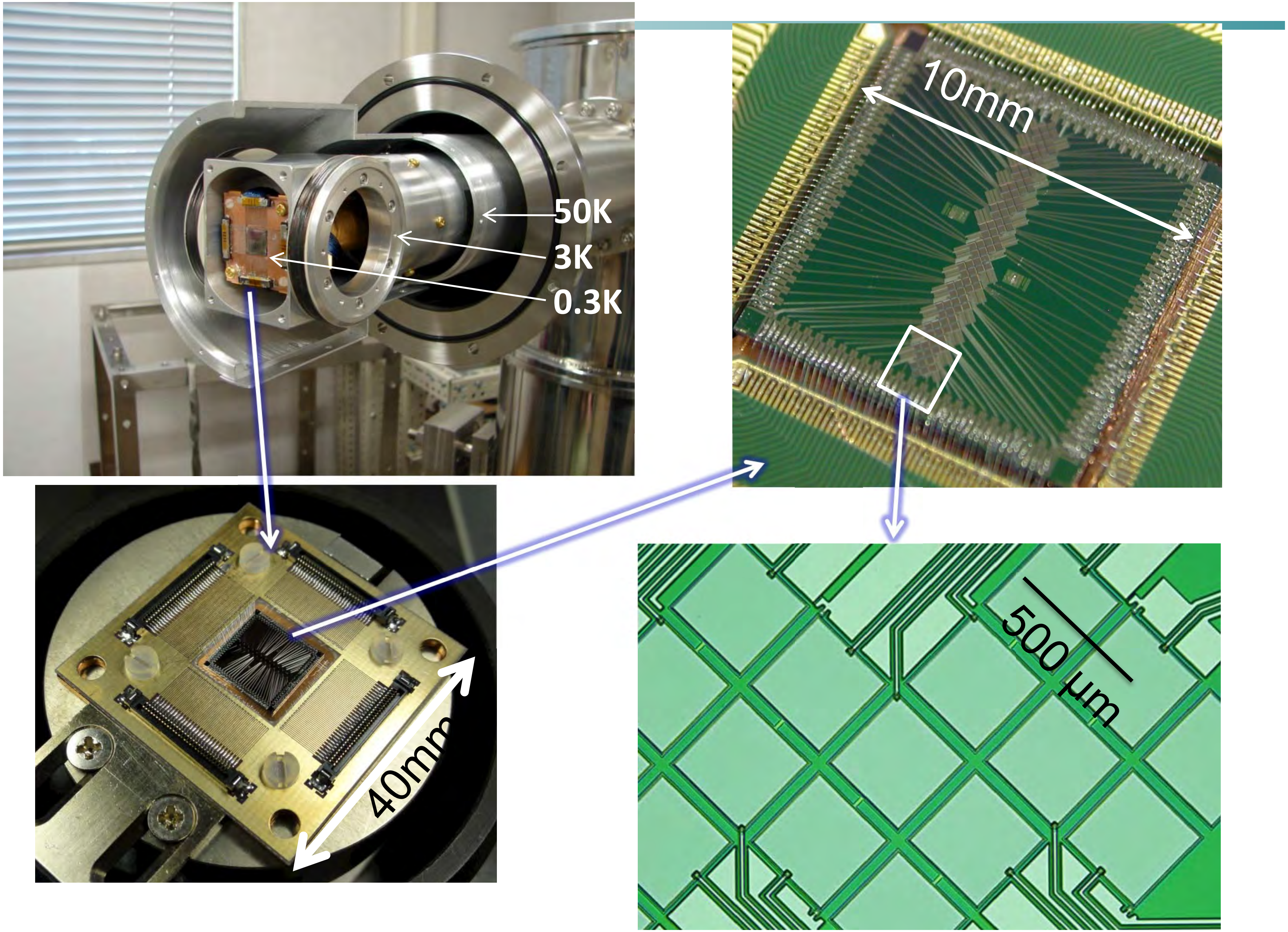
City of Tsukuba



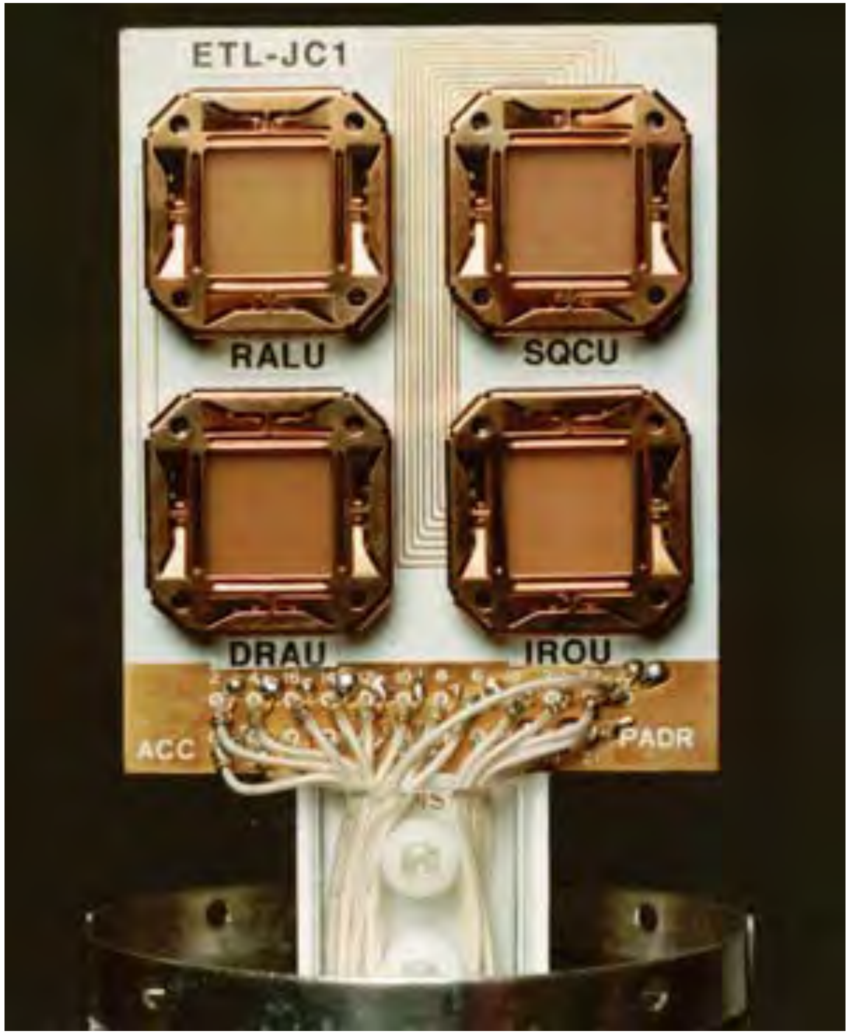



KEK PF BL13A
PF
BL-14Cmono
BL-14C
BL-14A
SR
STJ
It is in routine use.

Detector mount at 0.3 K



Electrotechnical Laboratory (ETL)



1986

Predecessor's milestone in superconductor electronics

Josephson computer - ETL-JC1

4-bit CPU with 1,000 bits RAM

Josephson computer technology

Recent advances on the road to superconducting computers include novel operating designs for logic and memory circuits as well as stable and reliable devices made entirely from refractory materials.

Physics Today 1986

Hisao Hayakawa

In 1962 Brian Josephson predicted that a current of superconducting electron pairs could tunnel through an insulating junction between two superconductors while maintaining the phase coherence of the pairs' wavefunctions on the two sides of the junction; the effect was soon experimentally verified. Such Josephson junctions can switch rapidly to the resistive state and have very low power dissipation, properties that suggest the application of Josephson junctions to computers. IBM started investigating superconducting computers, using Josephson junctions for memories and logic circuits, in 1964. Juri Matisoo and his colleagues at IBM demonstrated[1] a logic circuit with subnanosecond operation in 1966. At the time, this switching speed was very attractive, for it indicated that Josephson devices could be competitive with semiconductor devices.

On the basis of these encouraging results, IBM began an intensive research effort aimed at using Josephson devices as the basis for an ultra-high-performance computer. The device and system concepts formed during these investigations were quite different from those for computers based on semiconductor devices.

One of the most important achievements of the IBM research was the development[2] of a technology that made it possible to integrate Josephson junctions on a chip. The technique involves fabricating junctions from alloys of lead, indium and gold. Logic and memory circuits based on this lead-alloy technology had unique performance characteristics and attracted a great deal of attention worldwide. As a result, several institutes around the world—and especially in Japan—began to work intensively on digital Josephson applications around 1980. The Japanese work on Josephson devices is part of the larger effort to investigate candidates for the next generation of computer technologies—to replace, perhaps, the silicon-based technologies; other candidates include devices based on gallium arsenide and high-electron-mobility transistors.

In spite of these successes, IBM announced[3] in 1983 that it was ending its Josephson-computer project for two main reasons. First, Josephson devices were losing their comparative attractiveness because of the rapid progress of semiconductor technologies, and second, it was proving difficult to design a cache memory for a Josephson computer—a main effort for IBM at that time. The IBM decision has had a large impact on research on digital Josephson electronics as well as a secondary effect on other fields of Josephson electronics. However, some laboratories—mainly in Japan—have continued their efforts toward developing Josephson digital devices in the belief that the performance of Josephson devices is still superior to that of semiconductor devices and that superconductors provide us with a unique technology for constructing a high-speed digital system. In fact, the Japanese efforts are now opening a novel aspect of Josephson digital applications. Figure 1, for example, shows a logic circuit recently made in our laboratory entirely from refractory materials; the cover shows a detail of this circuit. In this article I will review the present state of the art in Josephson computer technology, including materials, devices and systems.

Operating principles

The principle behind Josephson switching devices is that the voltage across the junction depends on the applied current and magnetic field; a small magnetic field can decrease the Josephson current, causing a voltage to appear across the junction. Once a junction has become resistive, it remains so until the current through the junction is removed. In a Josephson

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0031-9228 / 86 / 0300 46-06 / $01.00

CRAVITY AIST

CR for **A**nalog-digital superconducti**VITY**

● Room1 (Class 100) : Lithography-room (90 m²)

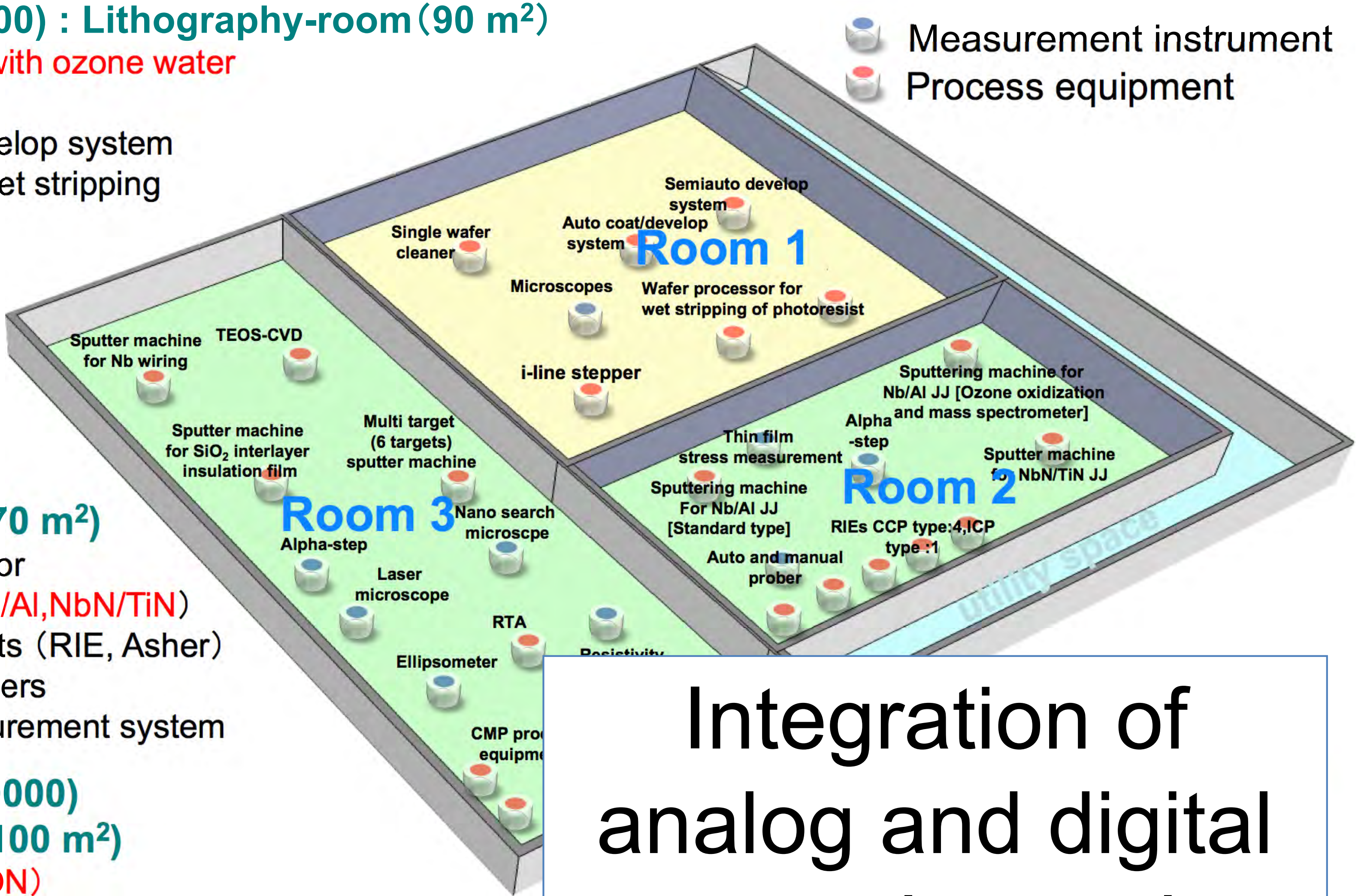
- Single wafer cleaner with ozone water
- i-line stepper
- Auto or semi coat/develop system
- Wafer processor for wet stripping of photoresist
- Wafer surface analyzer
- Microscopes

● Room2 (Class 1000-10000) :Deposition-room(70 m²)

- Sputtering machines for Josephson junction (Nb/Al,NbN/TiN)
- Dry etching equipments (RIE, Asher)
- Auto and manual probers
- Thin film stress measurement system

● Room3 (Class10000) :Deposition-room(100 m²)

- TEOS-CVD (SiO_2, SiON)
- CMP process equipments
- Nano search microscope

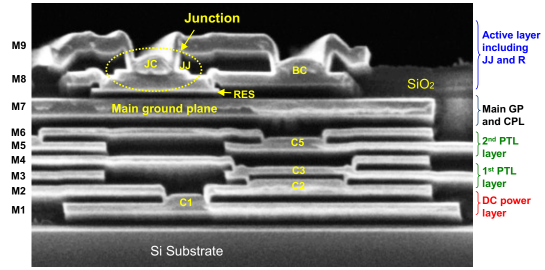


Integration of analog and digital super-electronics

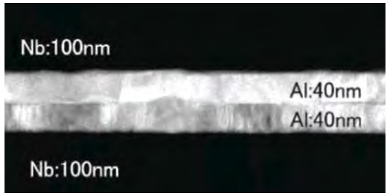
Standard wafer size: 3 inch

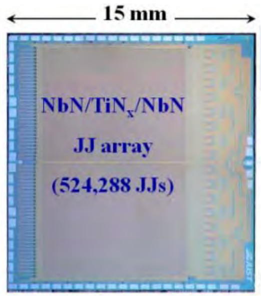
Technologies at CRAVITY

- Nb technology
  - ➢ 10-kA/cm^2 advanced process
  - ➢ 2.5-kA/cm^2 standard process
  - ➢ Low-leakage(0.1 pA/μm^2@200 A/cm^2) tunnel junction process

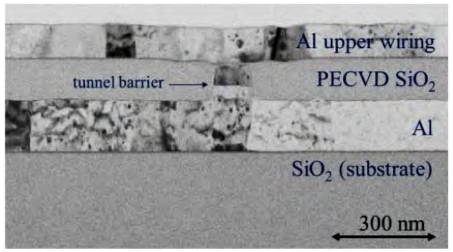


- NbN technology
  - ➢ SNS-junction process for 10-K operation

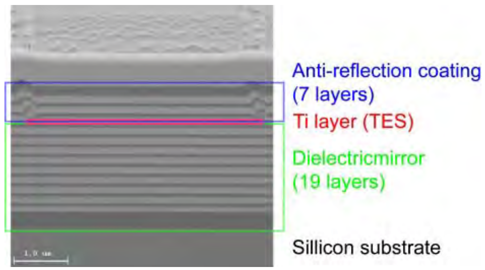




- Al technology
  - ➢ Deep sub-μ trilayer-junction process



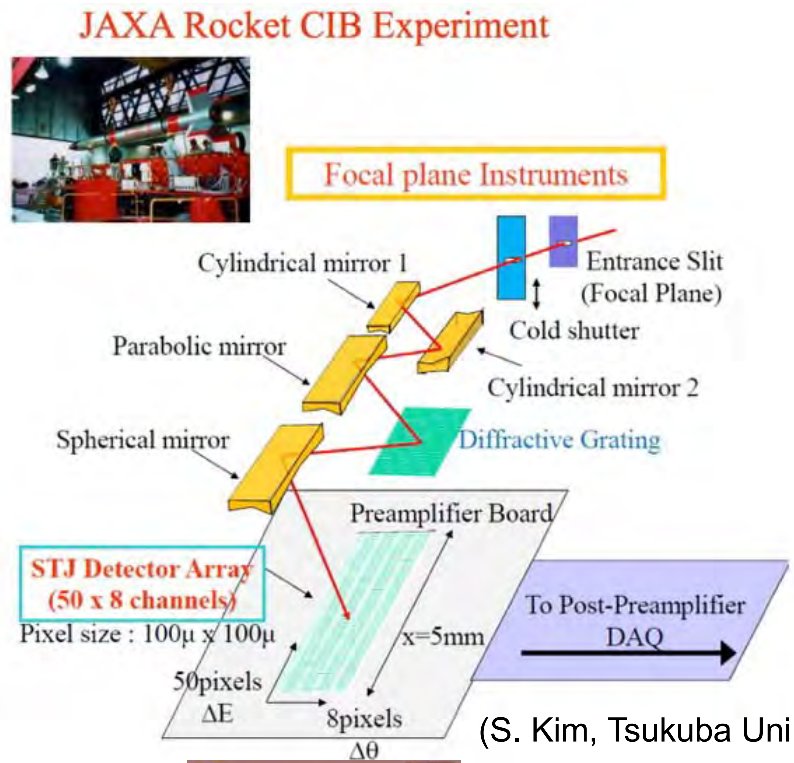
- Custom-made process
  - ➢ Cavity for IR photons



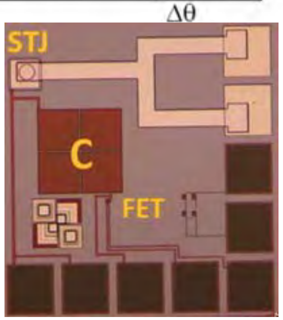
Applications of AIST-STJ detectors

Astrophysics

Determination of neutrino mass by
far-IR photon spectroscopy (15 - 30 meV)



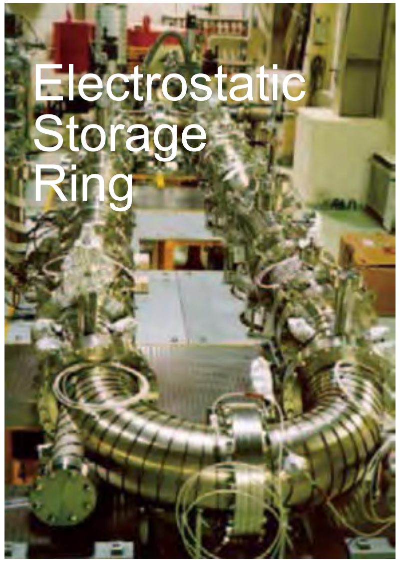
(S. Kim, Tsukuba Uni.)



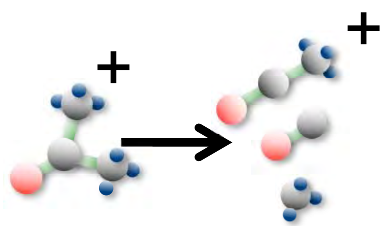
Focal plane STJ-SOI IR imager at 0.3K

Mass spectrometry

Interstellar chemistry (origin of life)
Escape of planetary atmosphere



N_2^{2+}
(2008)

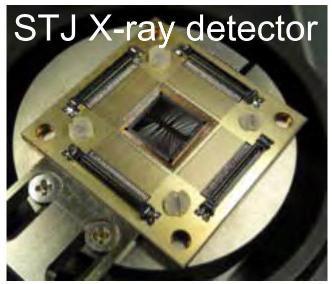


Neutral fragment analysis (2011)

(T. Tanabe, KEK)

Synchrotron radiation

Functional and structural materials
XAFS for trace light elements (N: SiC 2012)



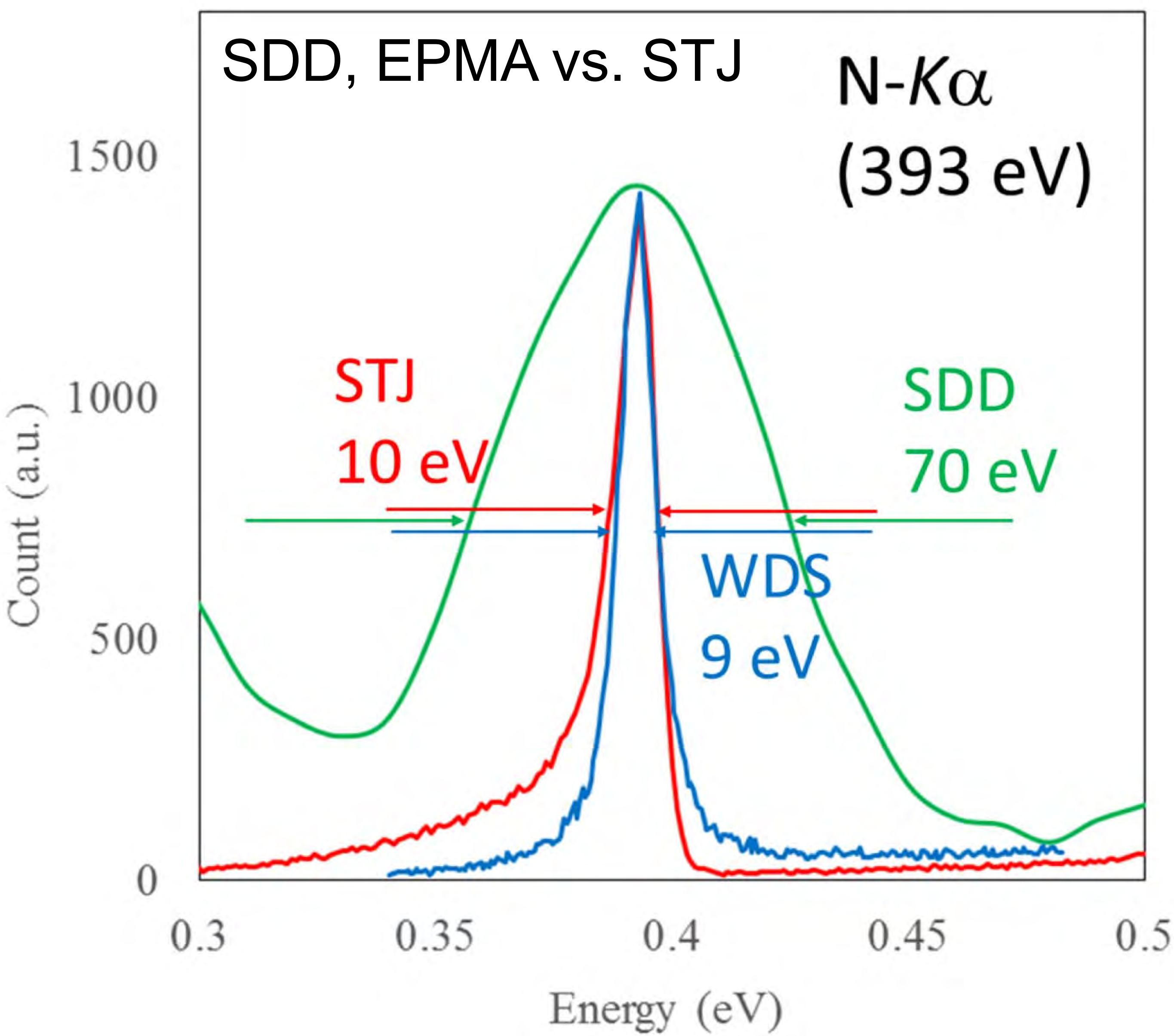
(K. Mase, Y. Kitajima, KEK)

Superconductor detectors

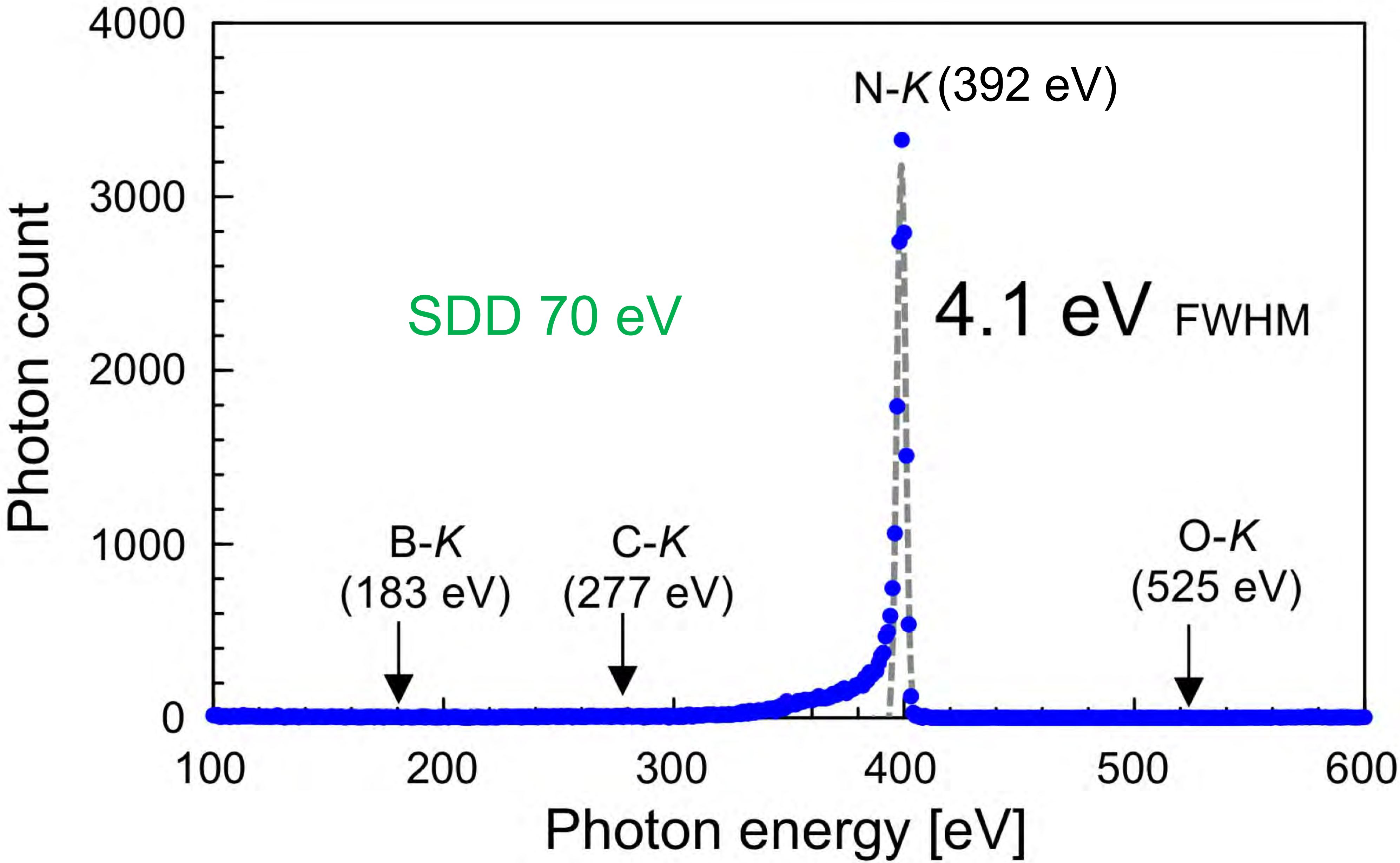
	Two spectroscopic domains		
Type	Energy	Time (decay)	Temp.
Calorimeter TES, MMC…	Extremely high (1.2 eV@ 6 keV)	Slow (ms)	< 0.1 K
STJ	High (4.1 eV@ 392 V)	Fast (μs)	0.3 K
SSPD (nano-strip)	N/A	Extremely fast (1 ns)	> 4.2 K

Third request: high spatial resolution for Taiwanese SR

High energy resolution is required for element selection and line shape

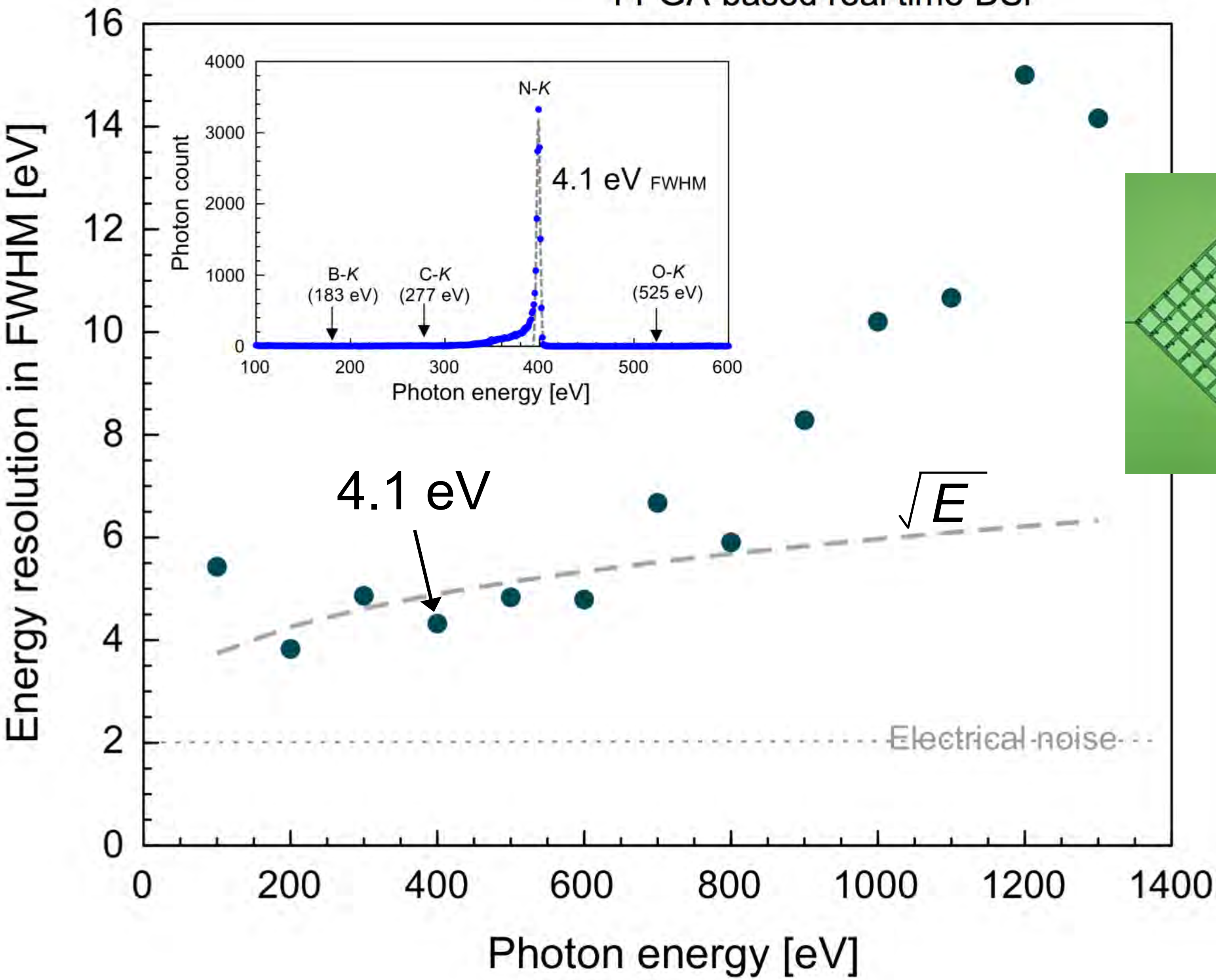


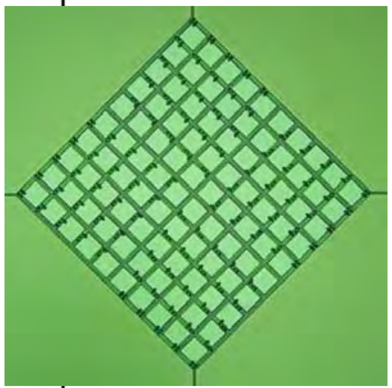
Real energy resolution @ synchrotron radiation



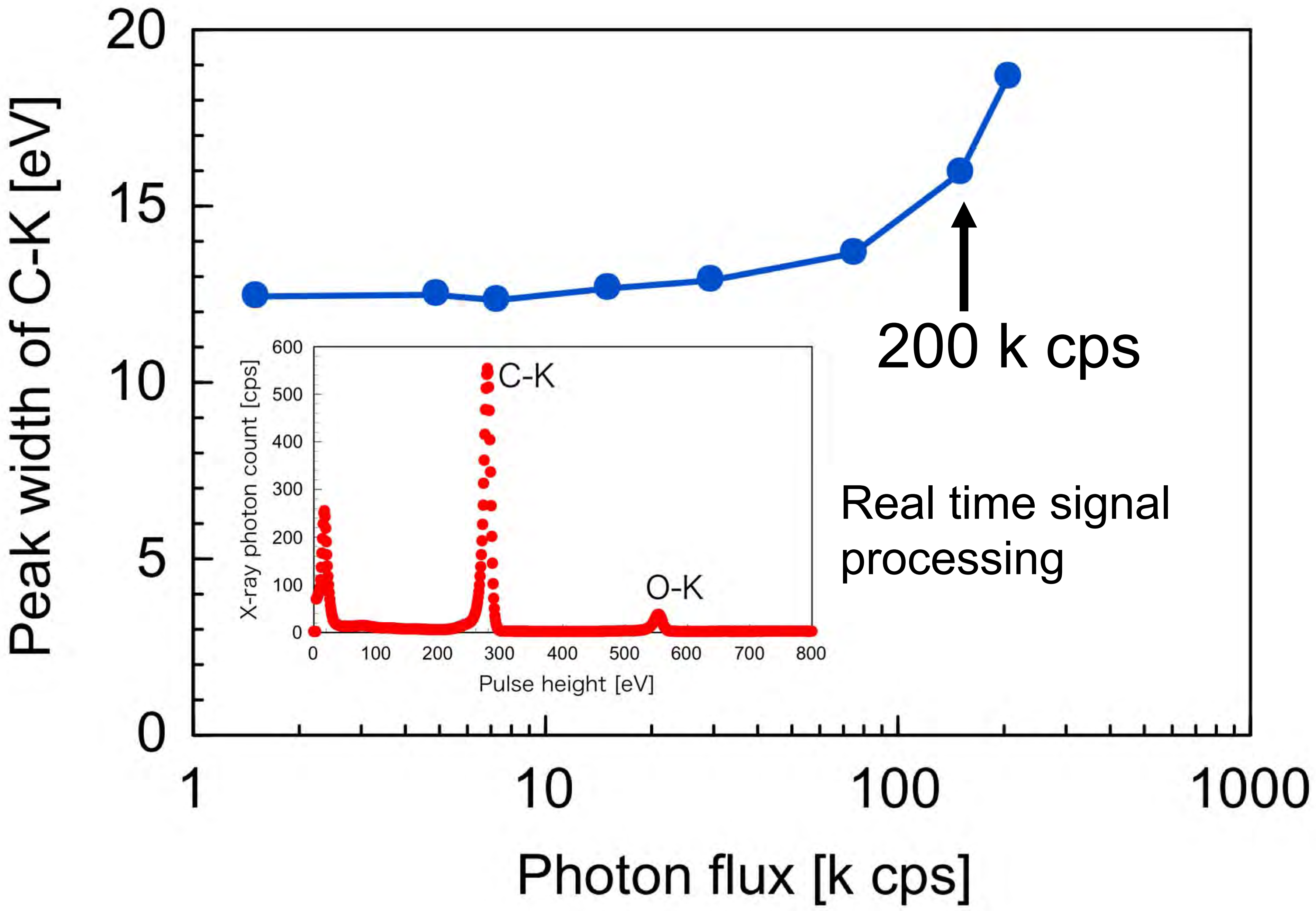
Energy resolution vs. photon energy of the best pixel

Synchrotron radition@400 eV
FPGA-based real time DSP

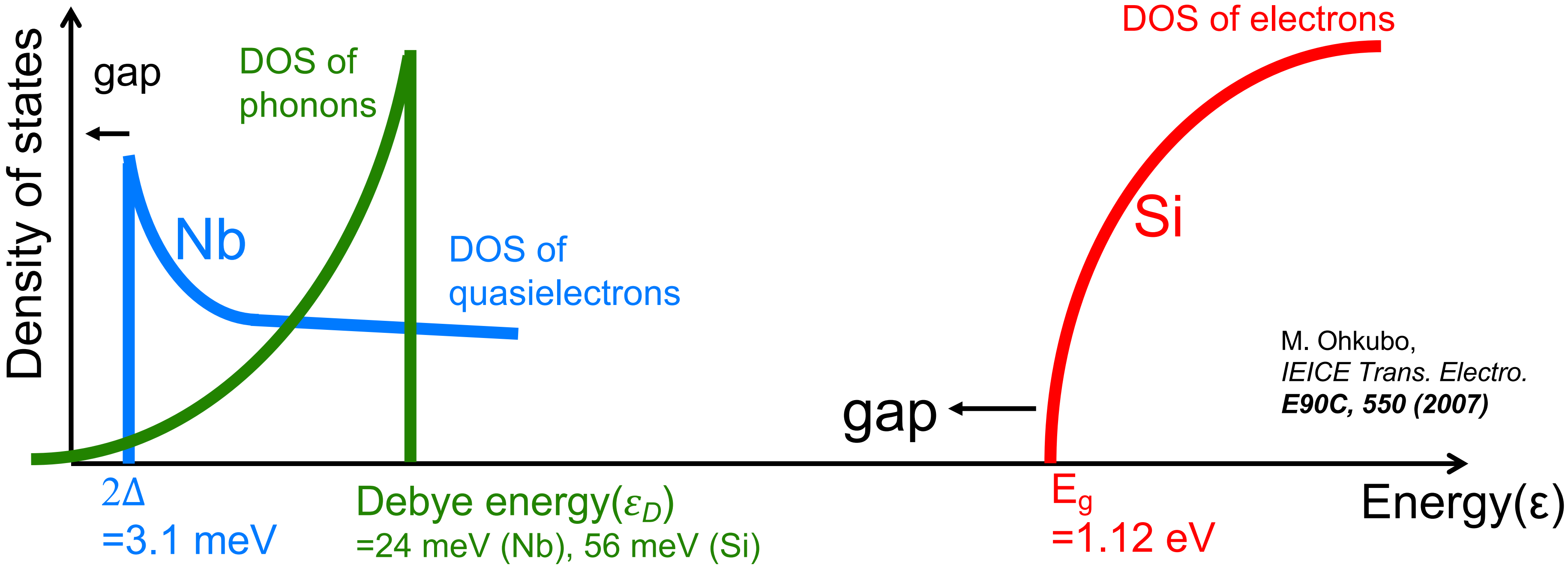


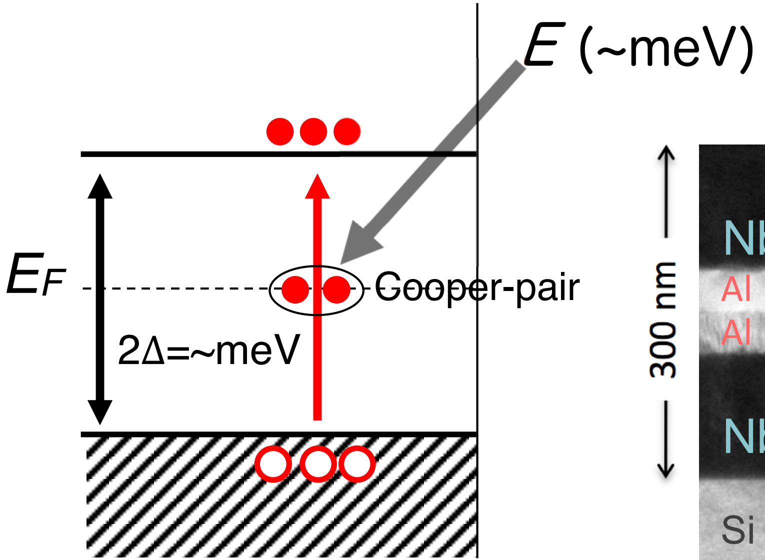


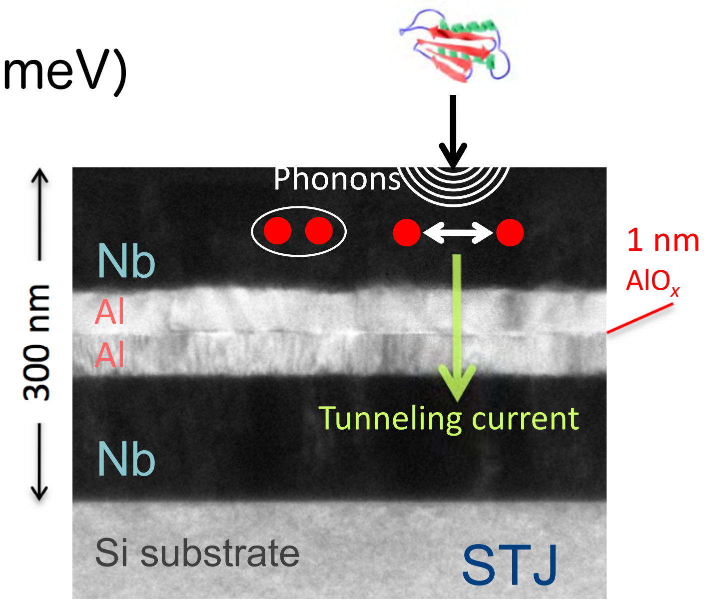
High count rate of the 100-ch STJ system

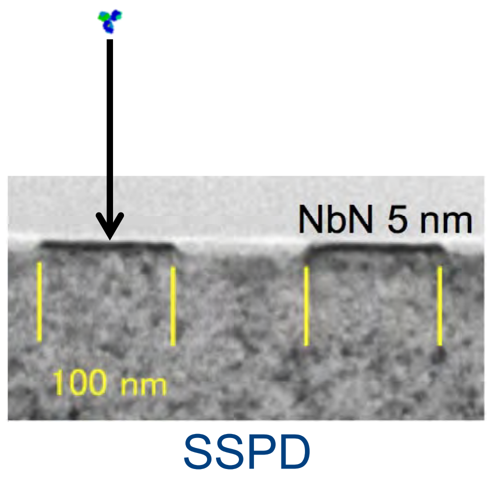


Comparison between super. and semi.









Theoretical limit of energy resolution in quantum detector

The ε value (a threshold energy to create quasiparticles) is1.7Δ, and the Fano factor is 0.195, M. Kurakado, NIM (1969).

ε = 1.7Δ = 2.6 meV in Nb (~ 1 eV in Si)

F = 0.195

$$\frac{\Delta E}{E} \propto \frac{\sigma_N}{\langle N \rangle},$$

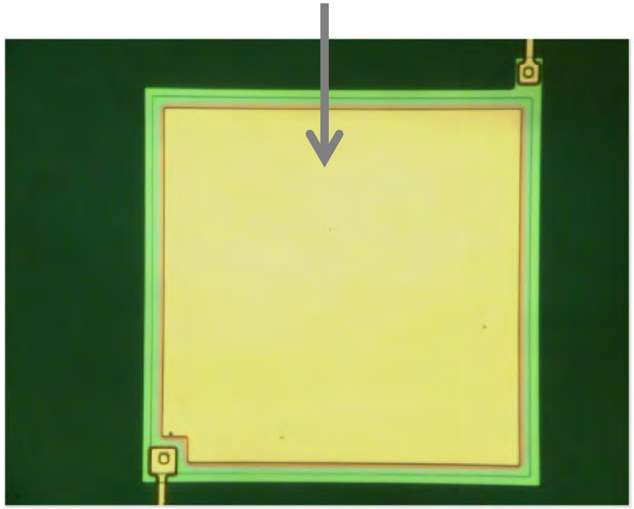
$$\Delta E_{\mathrm{FWHM}} = 2.355\sqrt{F\varepsilon E} =$$ 2 eV@6 keV(Mn-*K* line)

0.5 eV@400 eV (N-*K* line)

Photon counting rate = ~ 2 kcps/pixel

Quasiparticle tunneling

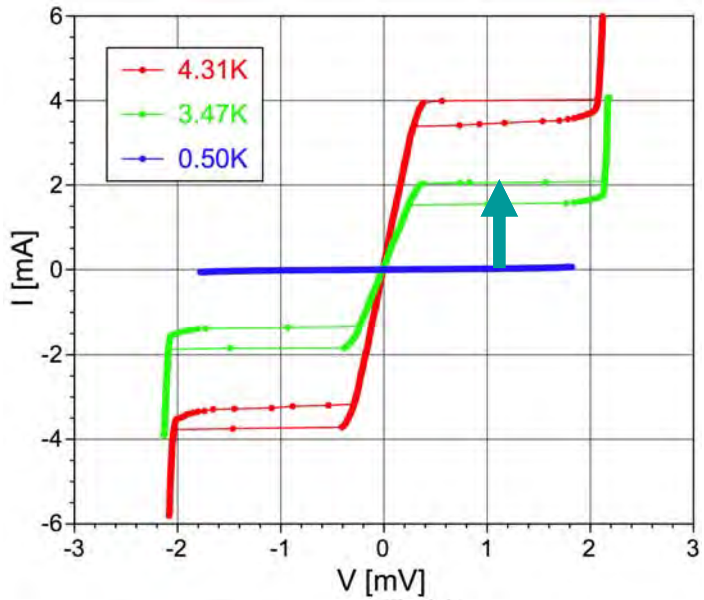
Soft x-rays

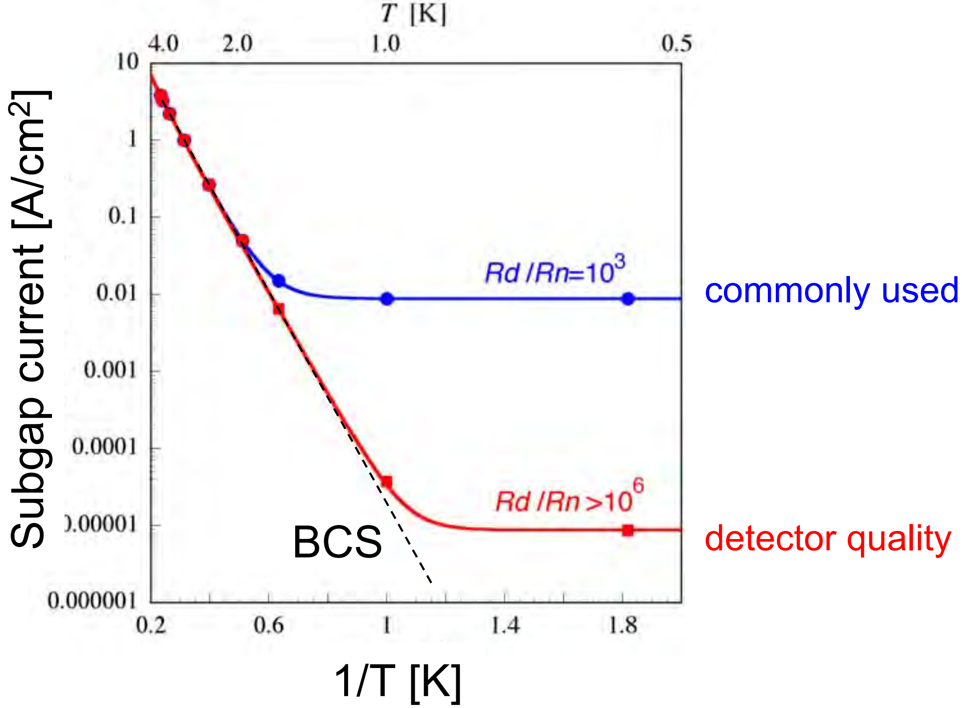


•Uncovered Nb electrode
(no contamination on surface is necessary.)

•Large junction (100 - 200 µm)

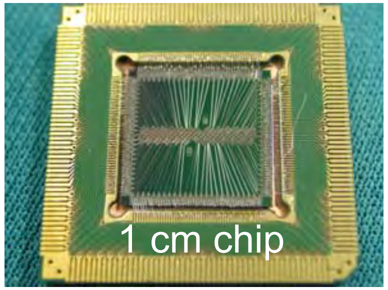
•Extremely low leakage current

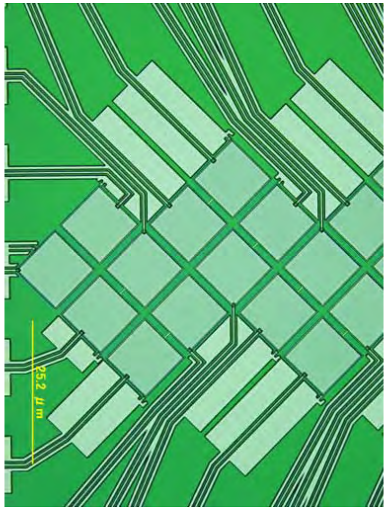




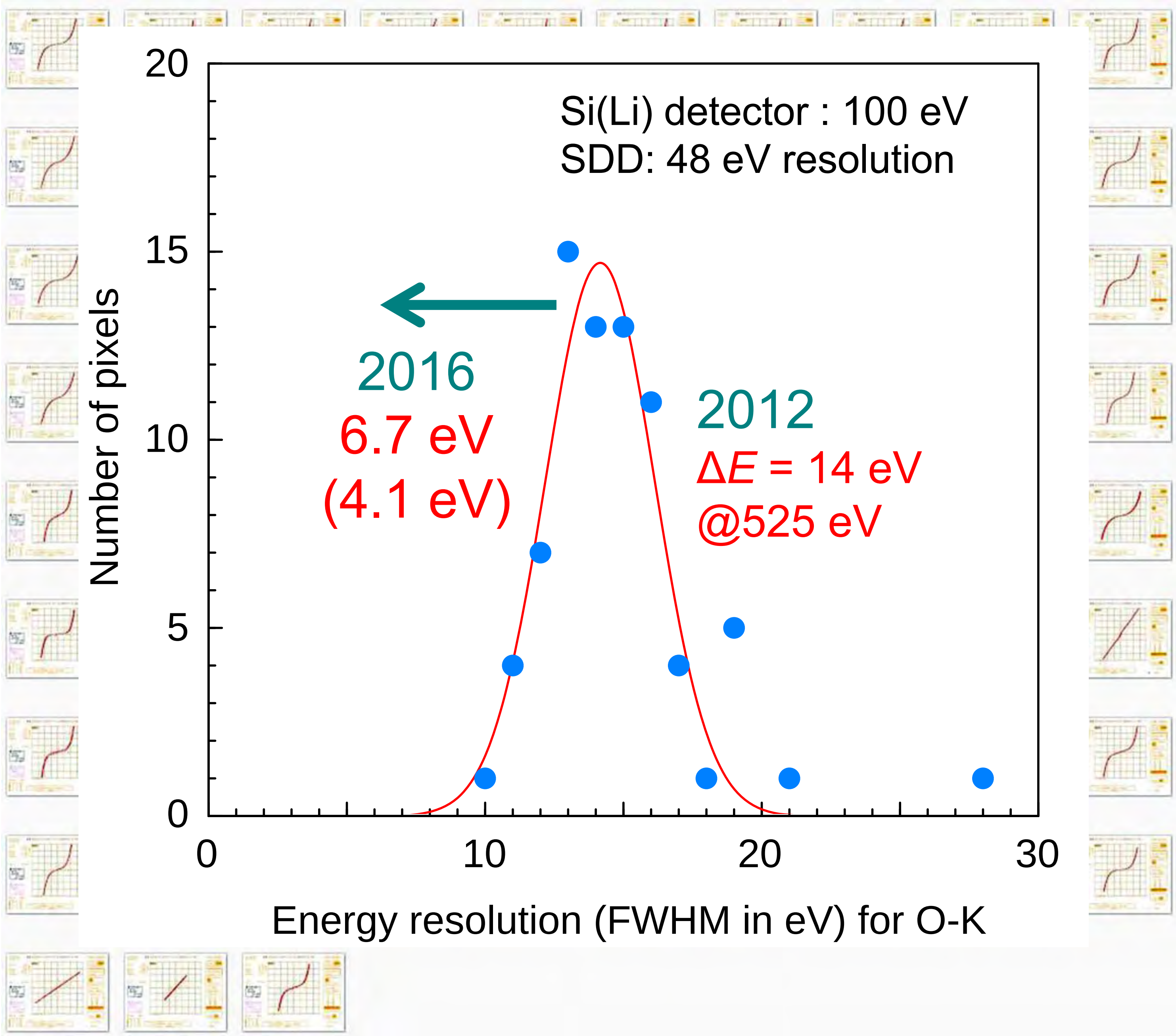
I-V curves of 100 STJs at 0.3K

Old 2D layout

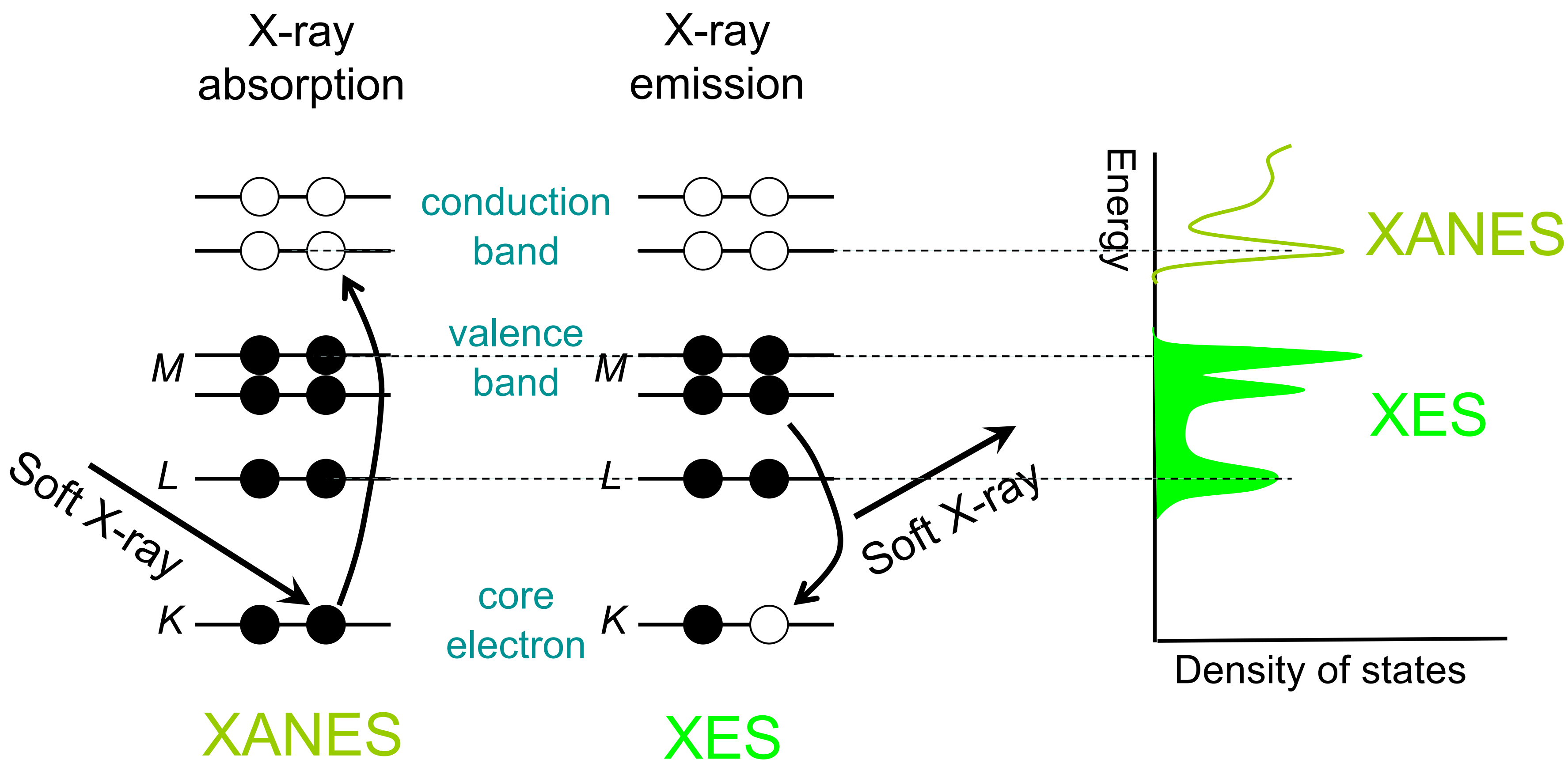




FPGA-DSP
(Cyclone III)



X-ray Absorption Near Edge Structure (XANES) and X-ray Emission Spectroscopy (XES)

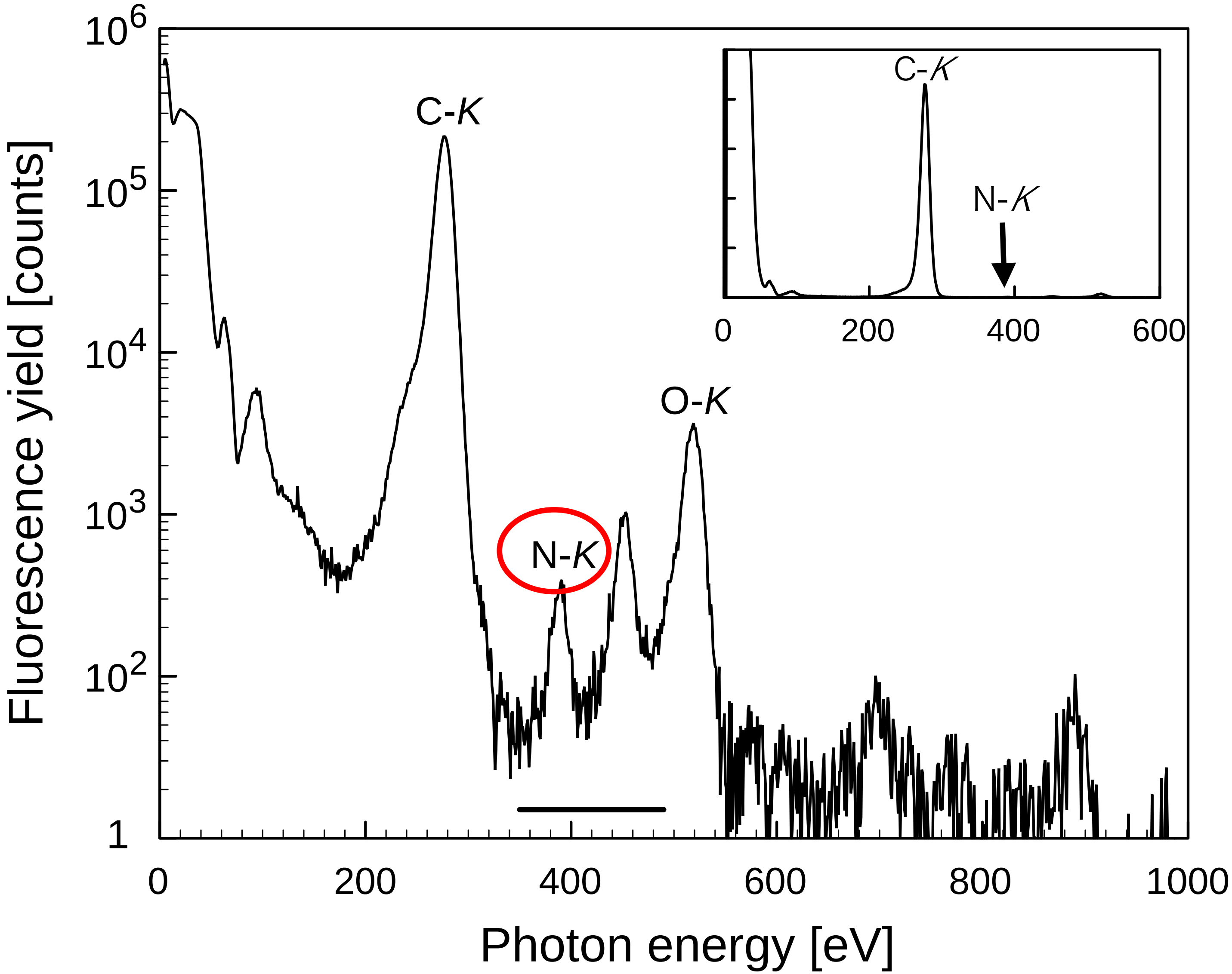


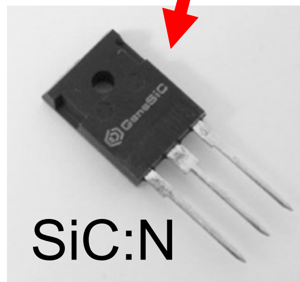
KEK PF
(FY-XAFS)

AIST STJ-SEM nanoimaging,
NSRRC TPS (SSPD-RIXS)

6 eV energy resolution with 200 kcps

Summation of 100 pixels data at 453 eV

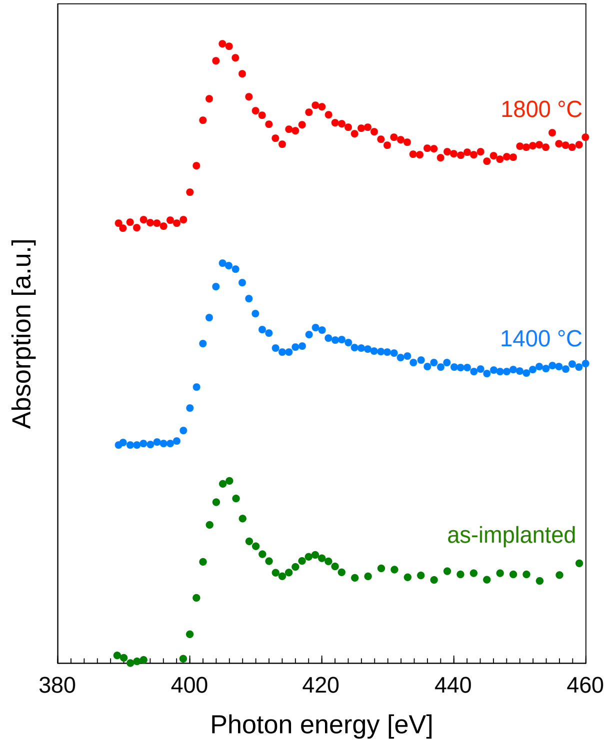




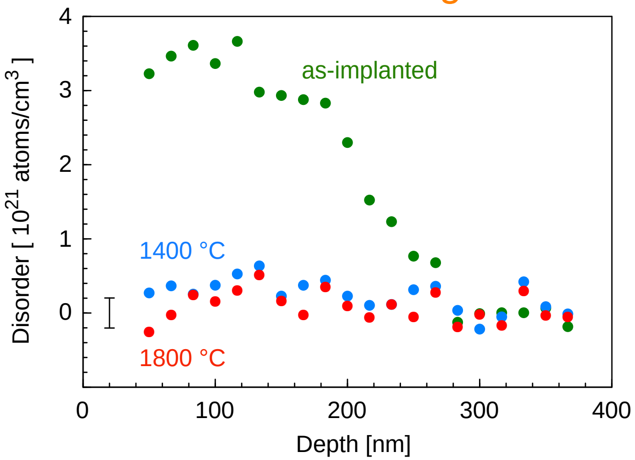
Nitrogen dopant (300 ppm) in SiC

XAFS of N dopant in SiC (4 x 10^{19} cm^{-3})

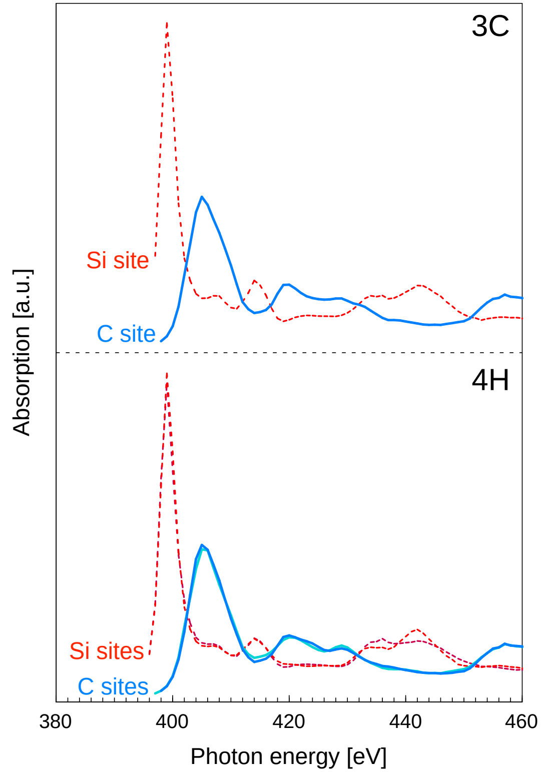
a XANES experiment



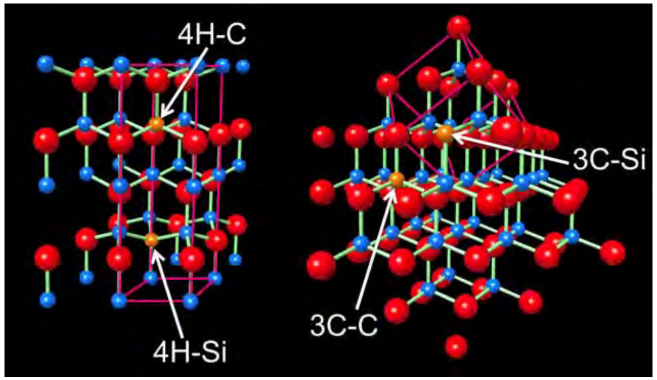
b Ion channeling



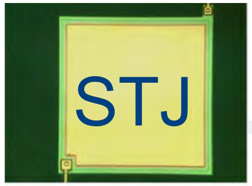
a First-principles calculation



b Substitution sites

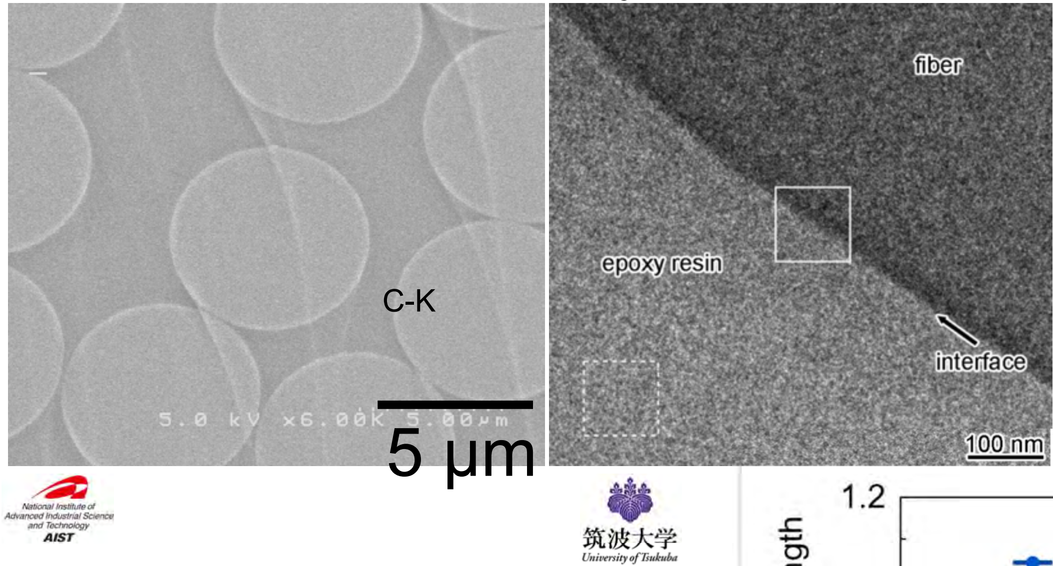


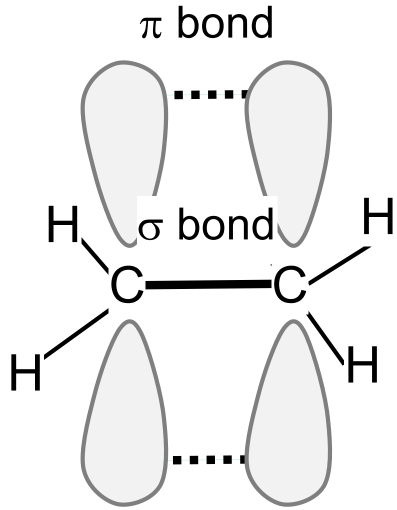
M. Ohkubo, *et al.*, Sci. Rep. 2, 831 (2012); DOI:10.1038/srep00831.

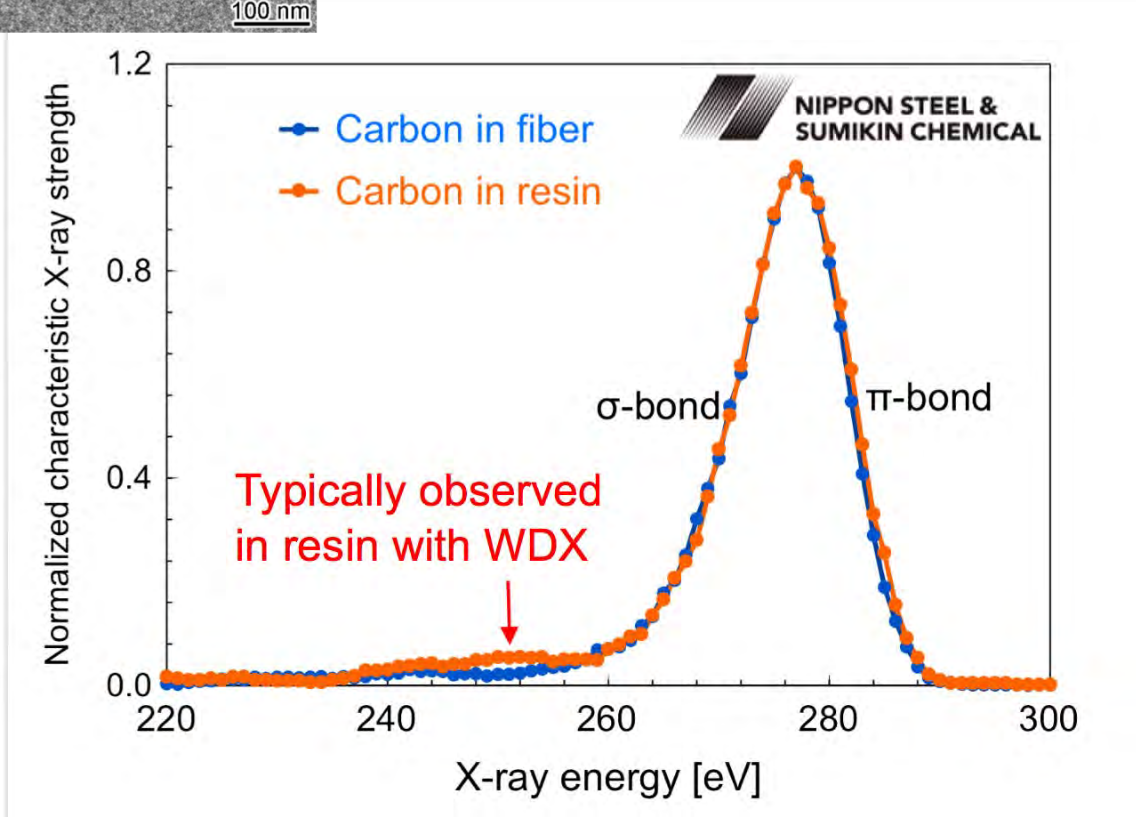


X-ray emission spectroscopy of C-*K*

Carbon fibre/resin boundary

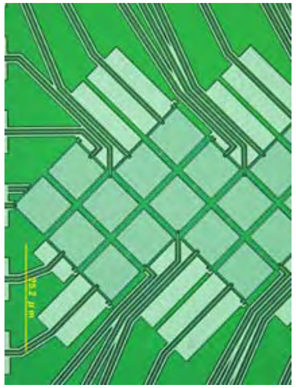




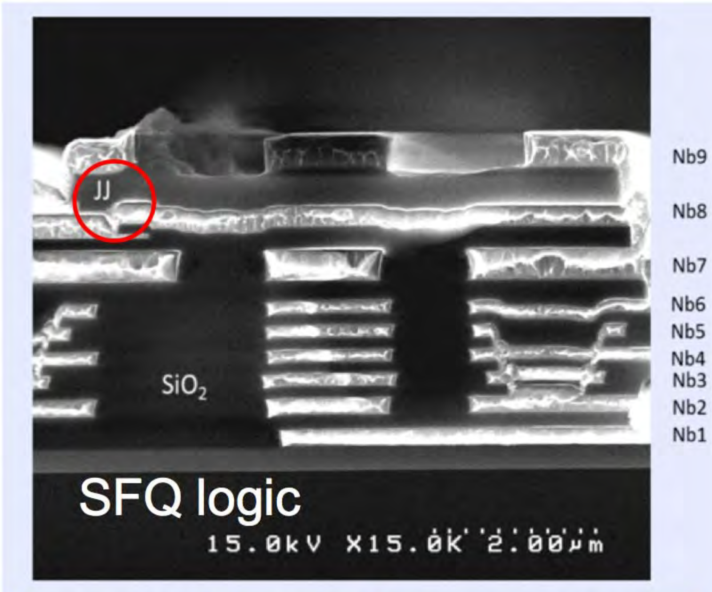


Latest STJ array detector for XAFS and PIXE

2D layout



➔

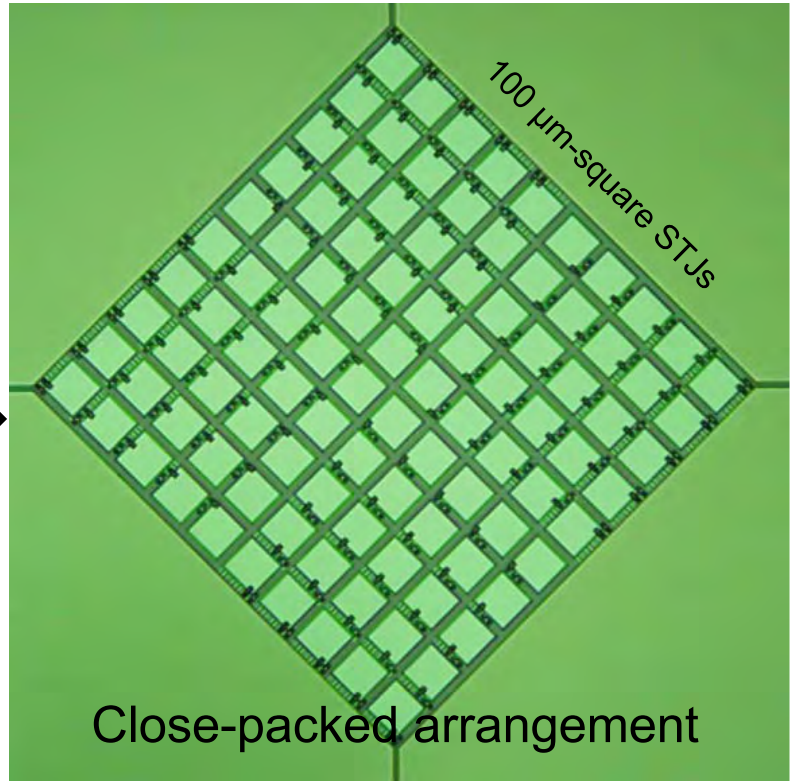


The number of Nb layers: 9
J_c: 10 kA/cm^2
Sheet resistance (R): 2.4 Ω

Minimum JJ size: 1 × 1 μm
Minimum line width: 1 μm
Stacked contact

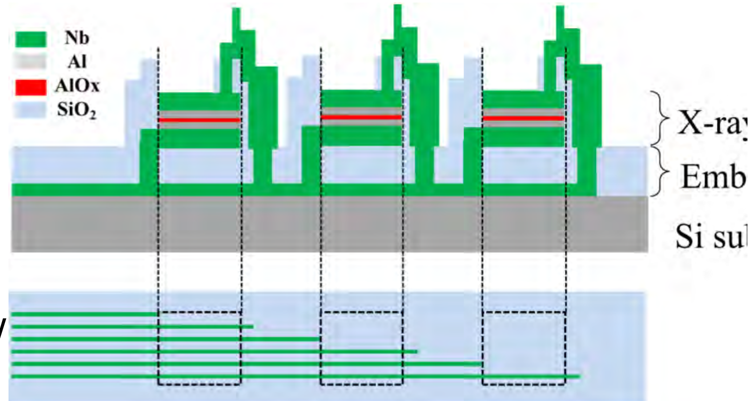
➔

3D layout



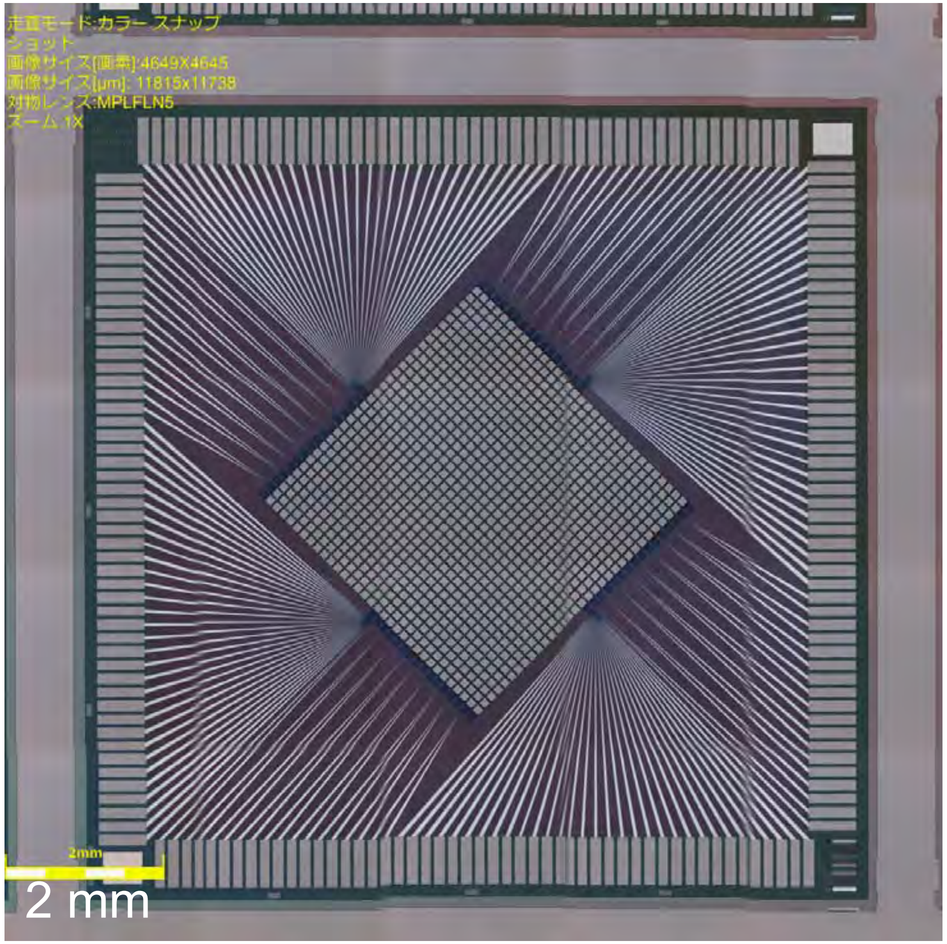
Cross section

Top view



G. Fujii *et al*., Supercond. Sci. Technol. 28, 104005 (2015).

Upgrade to 512-1024 pixels



G. Fujii and M. Ukibe 1024 pixels

6 MeV Van de Graff accelerator

筑波大学 University of Tsukuba

S. Shiki

Microbeam Particle-Induced X-ray Emission (PIXE) with 512 STJs and also for FY-XAFS

Summary of STJ

- SR: FY-XAFS for light elements (N: SiC, Mg:GaN, N_2:CFRP, B-C-N: heat resistant steel, B-C-N:Ti alloys,,,)
- Low-voltage SEM: < 10 nm spatial resolution in X-ray emission spectroscopy for light elements

  (carbon fibre/resin and CFRP/CFRP adhesion boundaries)

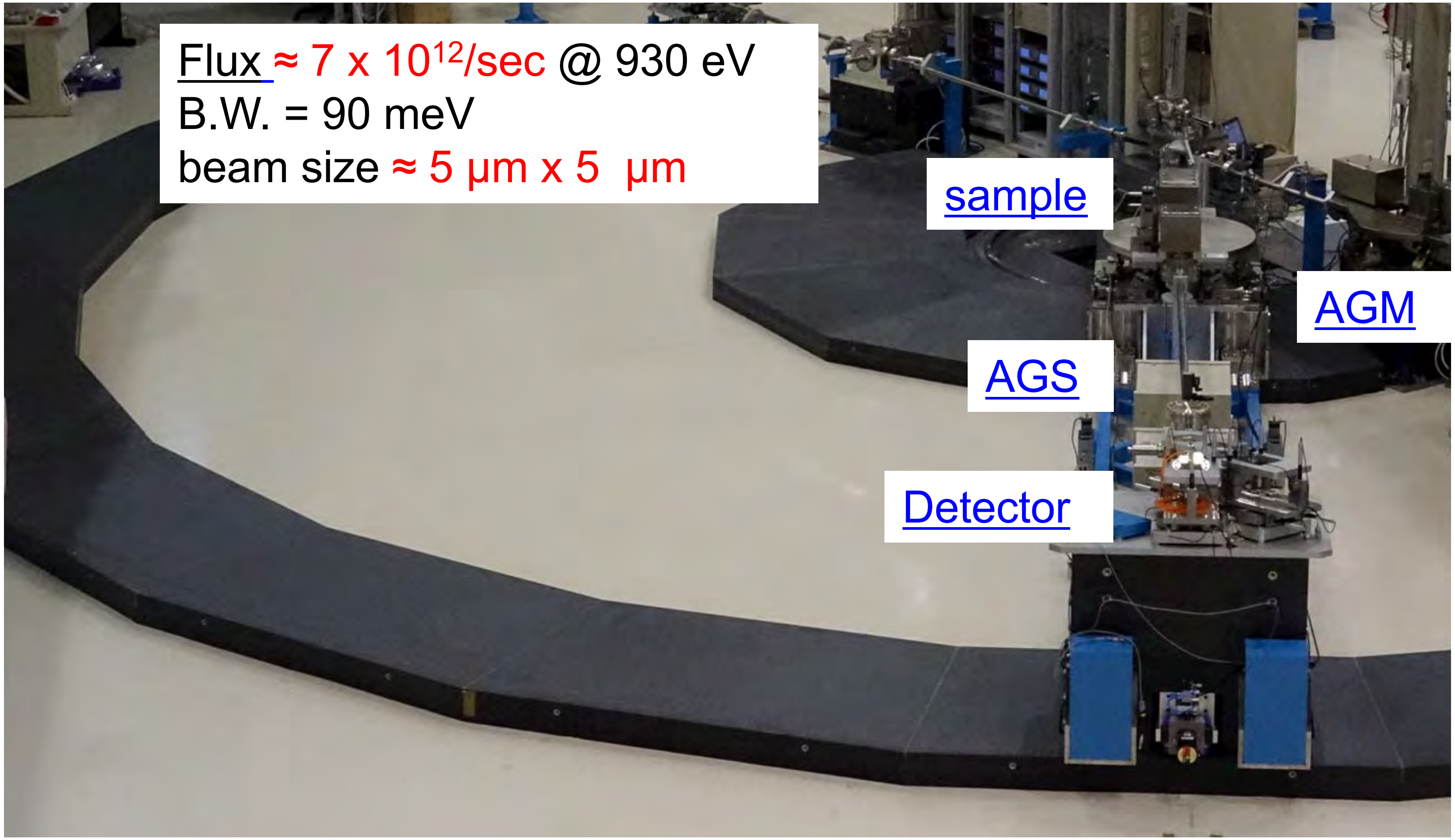
Taiwan Phton Source

New Resonant Inelastic X-ray Scattering (RIXS) Spectrometer @ TPS

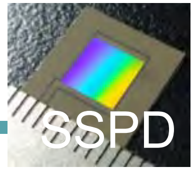
ΔE : 15 meV ➔ 5 meV

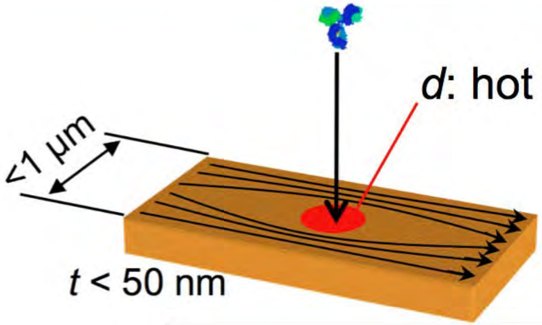
$E/\Delta E$: 20,000 ➔ 60,000

TPS 41A Soft X-ray Scattering

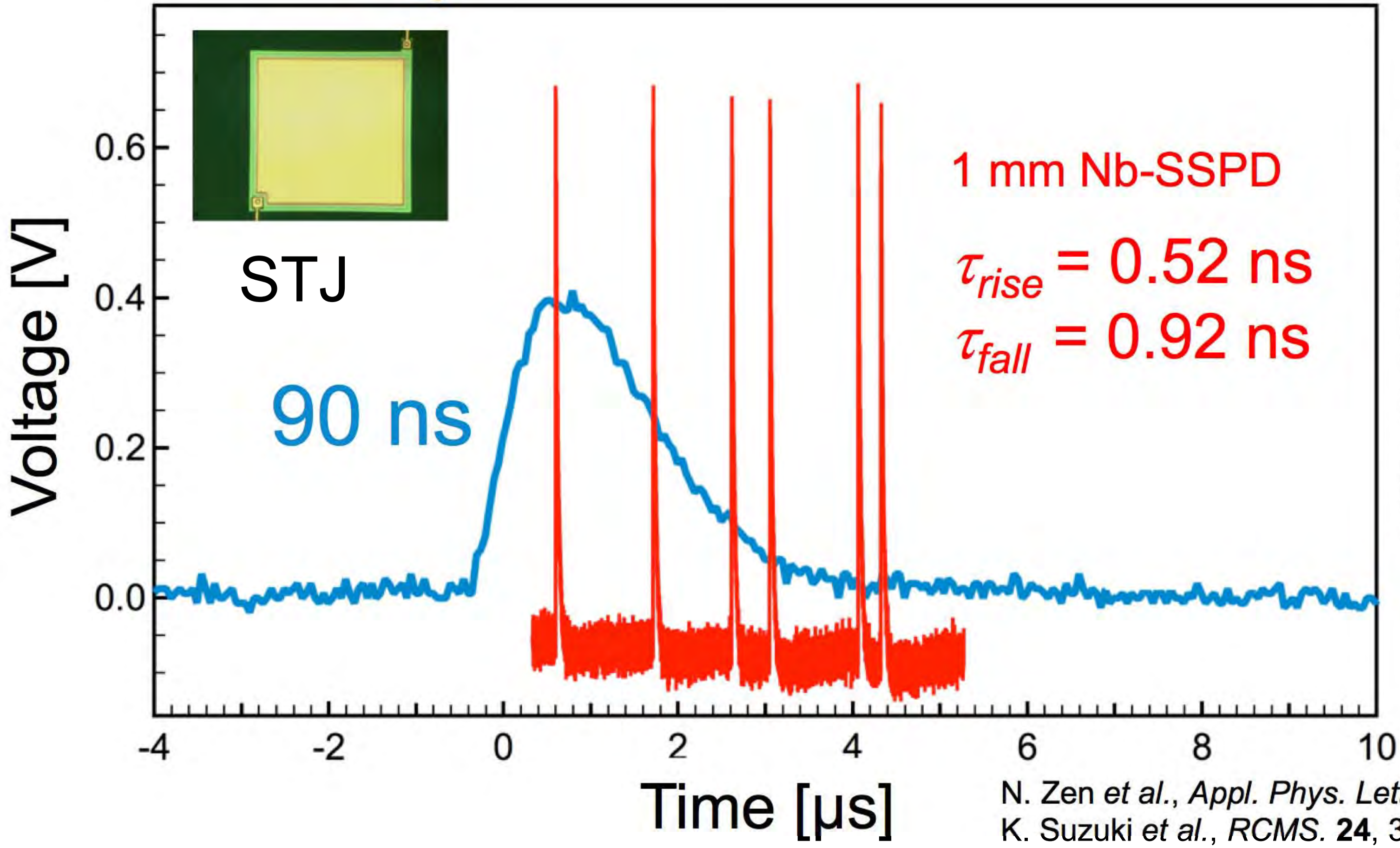


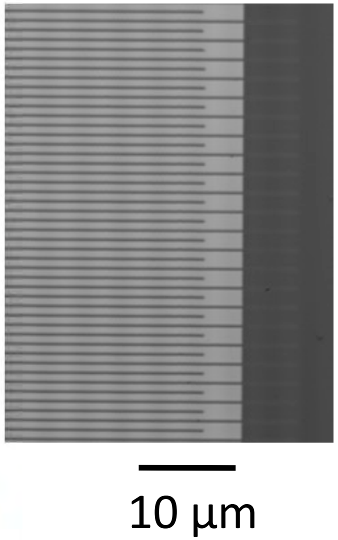
Time resolution and spatial resolution





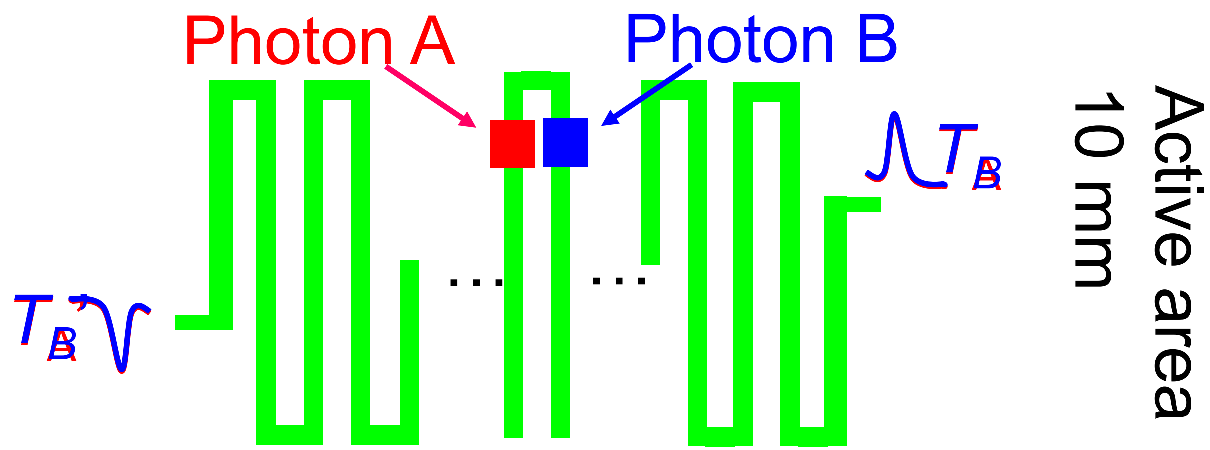
Kinetic inductance: $L_k = \mu_0 \lambda^2 l/S$

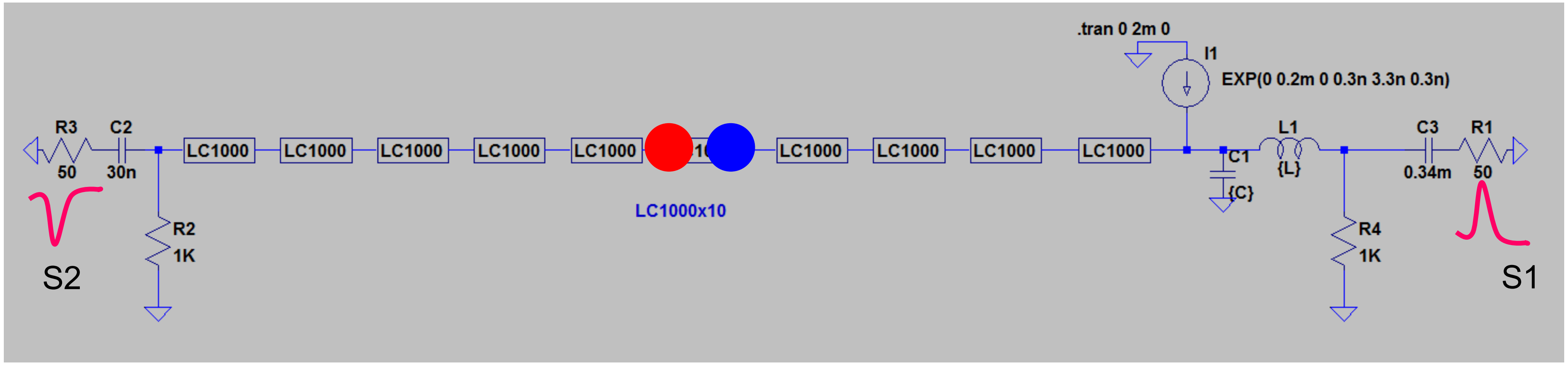




N. Zen *et al.*, *Appl. Phys. Lett.* **95**, 172508 (2009).
K. Suzuki *et al.*, *RCMS.* **24**, 3290 (2010).
A.Casaburi, *et al.*, *Appl. Phys. Lett.* **98**, 023702 (2011).
N. Zen *et al.*, *Appl. Phys. Lett.* **106**, 172222601 (2015).
R. Cristiano at al., SUST **28**, 124004 (2015).

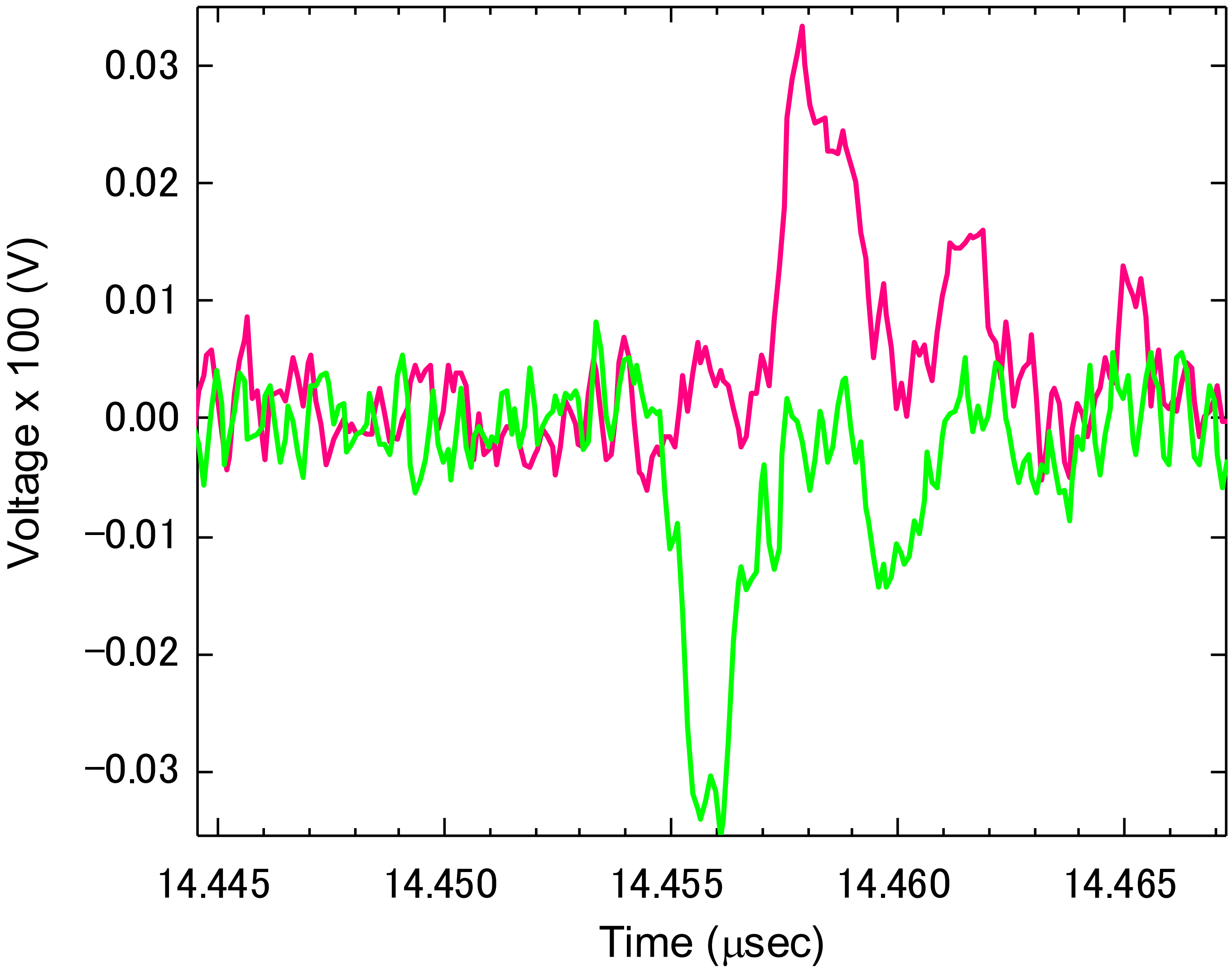
Soft X-ray photon imaging with delay line





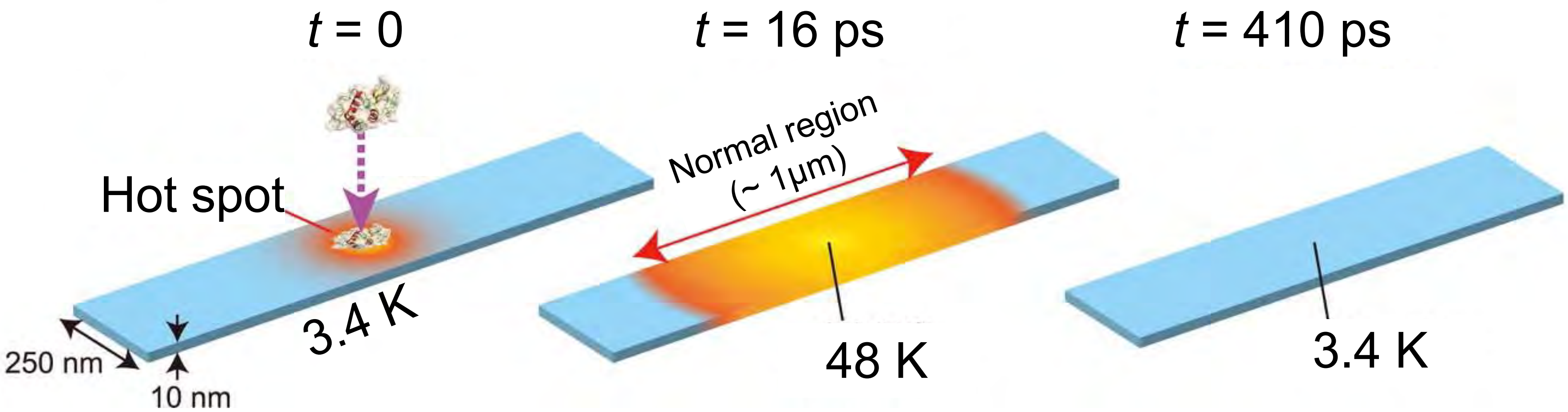
Experiment results – detection of ion

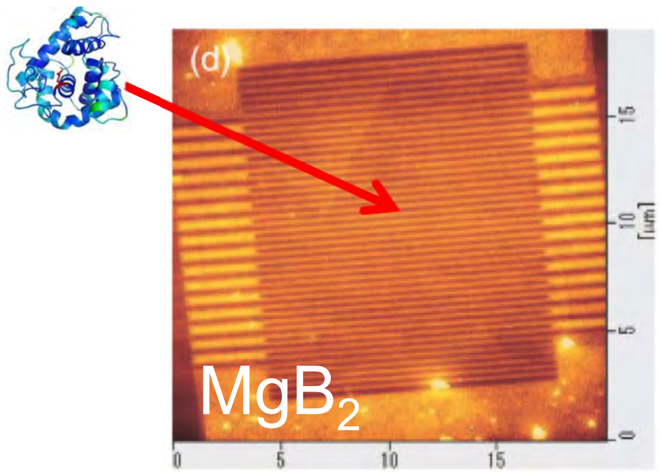
SSPD

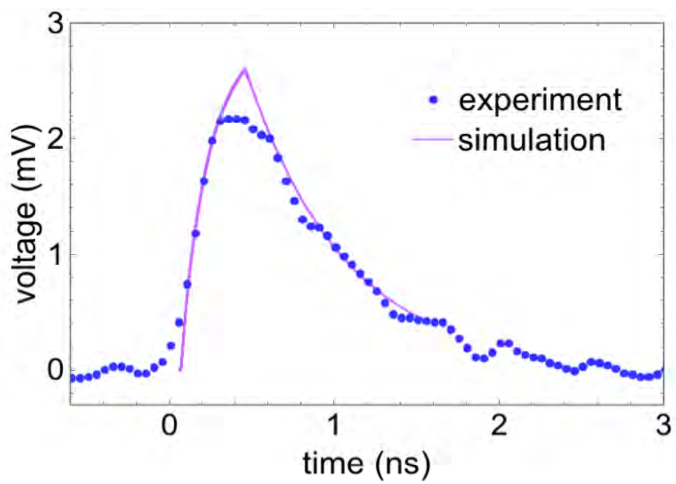


MB_2 temporal evolution

- Time-dependent GL with heat diffusion equation revealed the dynamical change of superfluid density, temperature, output voltage.
- Hot spot model is appropriate for 20 keV ions (not Voltex-Antivoltex Pair).



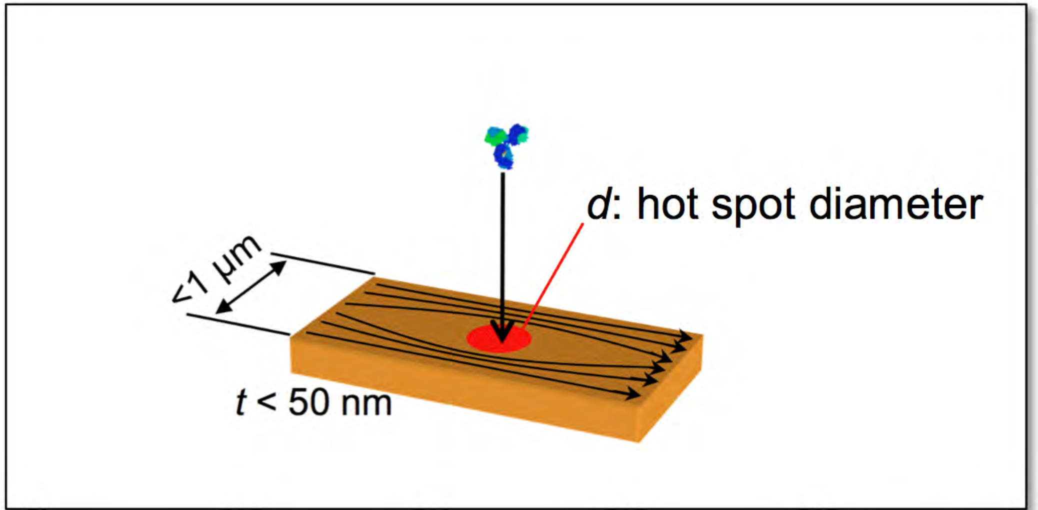


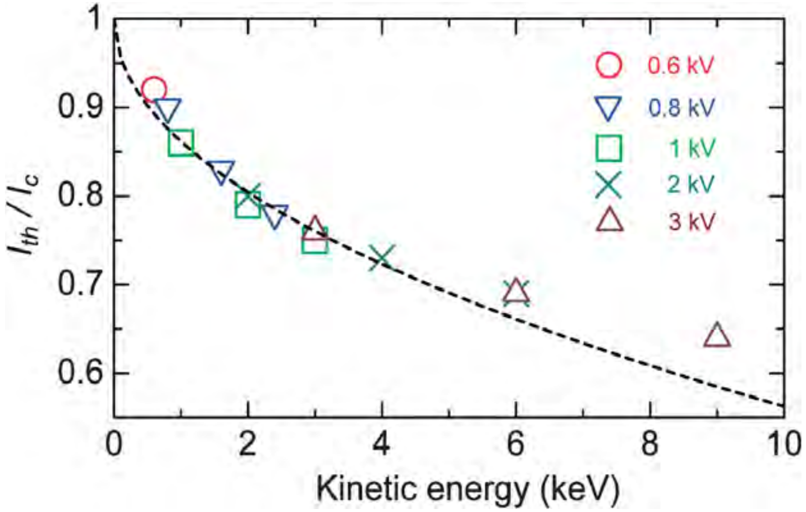


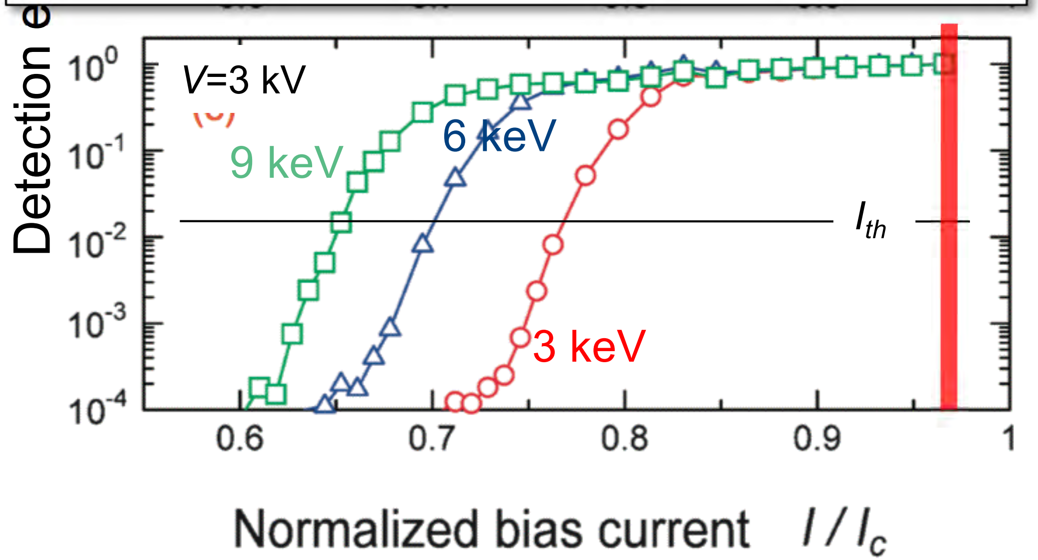
N. Zen, *et al.*, *Appl. Phys. Lett.* **106**, 222601 (2015).

Detection efficiency as a function of ion energy

NbN-SSLD: 10 nm-thick single-crystalline NbN with a line width (w) of 800 nm on MgO







- The hot-spot model
  I_{th}/I_c = 1- d/w (d : hot spot diameter region
  = $C \times (zV_a)^{1/2}$)
  It is assumed that the hot-spot volume is proportional to the ion kinetic energies.

- $C = 3.5 \times 10^{-9}$ eV$^{-1/2}$ m.
  (C = 11 - 20 $\times 10^{-9}$ eV$^{-1/2}$m for 1 eV photon)

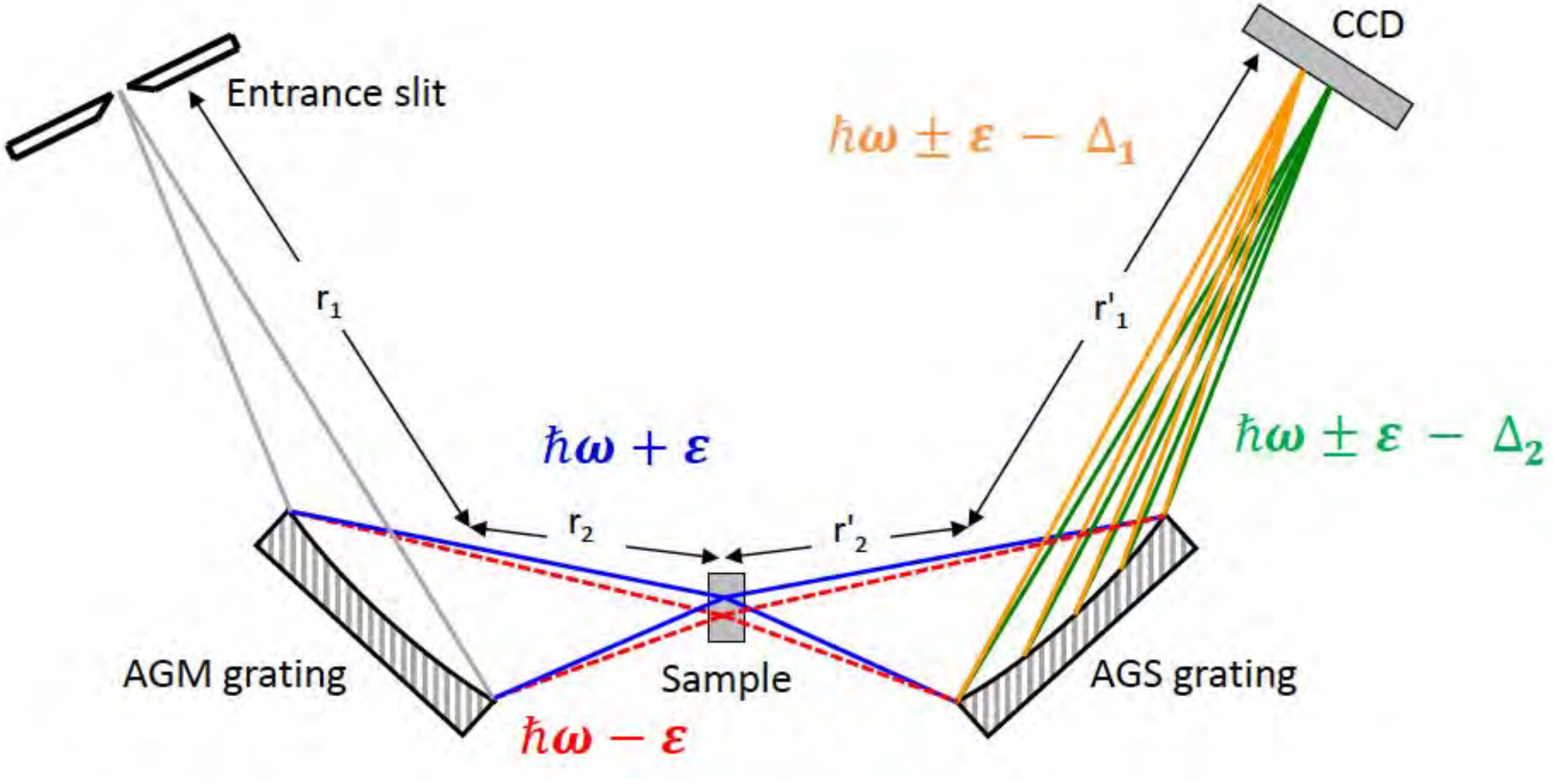
- The hot-spot diameter for 1 keV Ar^+ is 110 nm.
- A calculation for 5 nm NbN: 200 nm
  D. Perez de Lara, R. Cristiano, *et al.*, J. Low Temp. Phys. **151**, 771 (2008) LTD-12

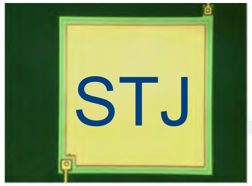
K. Suzuki, *et al.*, Applied Phys. Express **4**, 083101 (2011)

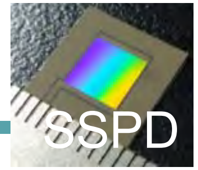
Focal plane SSPD imager

國家同步輻射研究中心
National Synchrotron Radiation Research Center

SSPD imager
(500 nm spatial resolution)







New trend of superconductor detector is emerging.

High energy resolution

High spatial resolution