New application stages of superconducting tunnel junctions in scientific instrumentation

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STJ detectors have a long history of more than 40 years. Many applications of STJ detectors have been proposed and some of them were not feasible for practical use as scientific instruments due to a low detection efficiency and a problem of thermal inflow and so on.

- Improvement of the fabrication technique CRAVITY (Clean room for analog-digital superconductivity)
  - Original techniques
    - Planarization process [Caldera process]
    - Oxidation process [Ozone process]
- Fabrication of advanced superconducting devices
  - A large scale STJ array with high performance (high $\Delta E$[G1.44], quite low leakage[G2.4], 3D-STJ[G1.42], SPA-STJ[G1.43])
  - Superconducting signal processor (SFQ-TDC) [G2.48]
Room1 (Class 100) : Lithography-room (90m²)
- Single wafer cleaner
- 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 (70m²)
- Sputtering machines for Josephson junction (Nb/Al, NbN/TiN)
- Dry etching equipments (RIE, Asher)
- Auto and manual probers
- Thin film stress measurement system

Room3 (Class 10000) : Deposition-room (100m²)
- TEOS-CVD (SiO₂, SiON)
- CMP process equipments
- Nano search microscope

Utility space (30m²)
- Supply equipment of process gases
- Vacuum exhaust units
- DI-water system
- Waste HF tank

Standard wafer size at every machine: 3inch

Access to https://unit.aist.go.jp/riif/openi/cravity/en/equipment/2-12expo.html#
Available technologies at CRAVITY

- **Nb technology**
  - 10-kA/cm² advanced process
  - 2.5-kA/cm² standard process
  - Low-leakage (0.1 pA/µm² @ 200 A/cm²) tunnel junction process

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

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

Available electronics at CRAVITY

**Analog devices**: STJ, SQUID, TES, and MKID

**Digital devices**: SFQ circuits, and qubits
Latest fabrication technology

Advanced process (ADP)

Planarization process (Caldera process)

Si Substrate

Conventional Process

 Nb 9-layer structure

Active layer including JJ and R

Main GP

2nd PTL layer

1st PTL layer

DC power layer
3D wiring for STJ detectors

2D-wiring
Filling factor
\( \sim 7\% \)

3D-wiring
Filling factor
\( \sim 70\% \)

\(10\, \text{mm} \)

\(10\, \text{mm} \)

\(\sim 1.3\, \text{mm} \)

\(100\, \text{mm} \times 100\, \text{mm} \) and \(> 120\, \text{mm} \)

\(\geq 5\) of wires: \(10/10\, \text{mm} \)

Number of the array

\(1000 \sim 10000\)

Sparse array

Closed-packed array
Present status of STJ detector

System energy resolution for 400 eV X-ray: 6.3 eV FWHM
Intrinsic energy resolution: 4.7 eV FWHM (Pulser: 4.2 eV FWHM)

The best energy resolution for Nb/Al STJ
7 times higher energy resolution than that of SDD

DR-P18: Go Fuji
Specifications and appearances

- Energy resolution of X-rays: 10 eV
- Energy range of X-rays: 100 eV - 15 keV (<2 keV: Nb/Al STJ array, >2keV:SSD)
- Pixel number: 100
- Maximum counting rate of X-rays: 1 Mcps
- Cooling: Automatic cryostat without a liquid helium (operation temperature: 0.3 K)

M. Ohkubo et al., *Scientific Reports*, 2, 831 DOI: 10.1038/srep00831 (2012).

Usage examples

Analysis of
- Trace light elements in wide gap semiconductor
- Na dopant in CIGS solar cells
- Mg dopant in LEDs.

Figure 1. XANES spectra of n-type dopant N atoms (300 ppm) in SiC in the as-implanted state and after annealing at 1400 or 1800°C.

Figure 2. Ab initio multiple scattering calculations. (a) XANES spectra calculated with FEFF8.424 for the N atoms in 4H- and 3C-SiC. (b) Crystal structure models of the N-doped
Application fields of SC detectors

Materials analysis: dopant analysis for developing functional and structural materials.

Space physics

Physical chemistry

Electrostatic Storage Ring

Mass analysis of neutral molecule fragments with dissociative recombination (DR)

Determination of neutrino mass

CMB
\[ n_\gamma = 411/\text{cm}^3 \]
\[ T_\gamma = 2.73 \text{ K} \]

CvB
\[ n_\nu = n_\gamma = \frac{3}{4} \left( \frac{T_\gamma}{T_\nu} \right)^2 n_\gamma \]
\[ = 56/\text{cm}^2 \]
\[ T_\nu = \left( \frac{4}{11} \right)^{3} T_\gamma = 1.95 \text{K} \]