Clean room for analog-digital superconductivity

- Specialized clean room for the fabrication and testing of analog/digital devices containing low temperature superconductors.
- Microfabrication of superconducting sensors and quantum signal processing.
- International innovation hub and open facility for companies, universities, and research institutes.
- Support for commercial ventures.

Outline

The CRAVITY complex is a micro-fabrication facility for users from universities, research institutes, and industry. Fabrication techniques are available for analog and digital superconducting devices, such as sensors and digital signal processing. To ensure highly productive fabrication of complicated analog/digital superconducting electronics, the majority of process machines are fully automated and the process parameters are determined by the latest knowledge and expertise.

Activities at CRAVITY

There are two primary modes of operation for CRAVITY clients: (i) clients can fabricate superconducting devices at CRAVITY by themselves, or (ii) clients can have the expert CRAVITY staff fabricate specific superconducting devices to order. To date, we have delivered approximately eight-thousand chips per year. CRAVITY is now playing a pivotal role as an innovation hub for superconducting electronics research, including quantum cryptography, quantum computing and sensing devices.

Superconducting devices made at CRAVITY

- **Digital devices**
  A number of digital devices have been fabricated, including 100k gates Adiabatic Quantum Flux Parametron (AQFP) (Fig.1), Single Flux Quantum (SFQ) high speed microprocessors with low power dissipation, digital/analog monolithic devices and quantum computing devices.

- **Analog devices**
  A number of analog devices have been fabricated, including Josephson voltage standard niobium-nitride (NbN) chip, Cryogenic Current Comparator, Microwave SQUID multiplexer (Fig.2), 4096 pixels Nb/Al Superconducting Tunnel Junction (STJ) array for soft X-ray detection (Fig.3), Superconducting Strip Particle Detector (SSPD), Transition Edge Sensor (TES) for quantum cryptographic communication.

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Apparatuses in CRAVITY

- **Room 1 (Class 100)**
  - Lithography-room (90m²)
    - Single wafer cleaner
    - i-line stepper
    - Auto or semi-auto coat/developing system
    - Wafer processor for wet stripping of photoresist
    - Wafer surface analyzer
    - Microscopes

- **Room 2 (Class 1000-10000)**
  - Deposition-room (70m²)
    - Sputtering machines for Josephson junction (JJ) (Nb/Al, NbN/TiN)
    - Dry etching equipment (RIE, Asher)
    - Auto and manual probers
    - Thin film stress measurement system

- **Room 3 (Class 10000)**
  - Deposition-room (100m²)
    - TEOS-CVD (SiO₂, SiON)
    - CMP process equipment
    - Nano search microscope

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**Room 1**

- Single wafer cleaner
- Auto coat/developing system
- Wafer processor for wet stripping of photoresist
- Microscopes
- i-line stepper

**Room 2**

- Sputtering machine for Nb/Al JJ (Ozone oxidation and mass spectrometer)
- Alpha-step
- RIEs CCP type:4, ICP type:1
- Thin film stress measurement system

**Room 3**

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

**Utility space**

- Measuring instrument
- Process equipment

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**Room 1**

- Sputtering machine for Nb/Al JJ
- Multi target sputter machine
- Alpha-step
- Laser microscope
- Auto and manual prober
- RTA

**Room 2**

- TEOS-CVD (SiO₂, SiON)
- CMP process equipment
- Nano search microscope

**Room 3**

- Sputtering machine for Nb/Al JJ
- Alpha-step
- Laser microscope
- Ellipsometer
- Resitivity mapping system
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- Nb-multi-layer device fabrication using a unique planarization method.
- The CRAVITY facility has delivered SFQ circuits consisting of tens of thousands of JJs that exhibit perfect operation.
- Fabrication and supply of superconducting devices to domestic and international institutes.

Superconducting digital and related devices

We are improving the Nb/Al based fabrication process, used to create superconducting digital circuits, and expanding this technology to fabricate other superconducting devices. We supply domestic and international institutes that demand superior superconducting devices using CRAVITY and provide technical advice. Leading edge devices are developed in close consultation with fabrication and design researchers. CRAVITY will continue to contribute to the development of superconducting electronics through these activities.

Activity

We are fabricating superconducting devices using a Nb-multi-layer fabrication process that has been developed for superconducting single-flux-quantum (SFQ) circuits. We are investigating the implementation of low-power and large-scale SFQ circuits and analog circuits, such as SQUID arrays to readout superconducting detectors. Our fabrication technology and expertise is continuously evolving to realize our clients ideas. For example, 3-D devices are fabricated using multi-layer technology. We focus on the fabrication of reliable and practical devices with short fabrication times.

Superconducting device fabrication

We supply fabricated superconducting devices to approximately 15 institutes as well as the AIST. Many research papers have been published and some practical uses are emerging using devices supplied from CRAVITY. There are many examples of successful research proposals and budgets based on CRAVITY use. CRAVITY is functioning as a superconducting device fabrication facility and will expand on these activities and play a key role in both Japanese and international superconducting fabrication for research and commercial use.

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- Fabrication of large scale superconducting quantum annealing devices
- Development of scalable device structure to realize beyond one million qubit devices
- Integration of different kinds of chips by 3D mounting technologies

Scalable superconducting quantum annealing device

Practical superconducting quantum annealing machines must be required with more than one million qubits. However, the number of qubits on a single chip is limited to several tens of thousands due to the limitation of fabrication processes. We propose a multi-chip device structure called QUIP (Qubit-chip/Interposer/Package-substrate) to realize a qubit number size scalability. We think the QUIP architecture is the best solution for realizing a practical annealing device.

QUIP structure

Qubit chips consisting of qubits and couplers are flip-chip-connected to active interposers, which include readout and control circuits, flip-chip-mounted on a package substrate with electrical signal lines and I/O pads. Circuits on the top surface of the active interposer are connected by Si vias (TSVs) in the active interposer and a bridge interposer to the peripheral circuits and to the adjacent active interposers, respectively. We estimated a quantum annealing device consisting of one million qubits was implemented on a 90 mm square package substrate by using the QUIP architecture.

Fabrication technologies for QUIP

We are developing Nb-based superconducting quantum annealing devices by utilizing the digital circuit fabrication process. Qubits with couplers and peripheral circuits are placed on different chips and connected by flip-chip bonding. Planarized three Nb layers for superconducting loops and wirings and Nb/AlOx/Nb Josephson junctions (JJ) are used for the qubit chips. For reducing noise sources, the JJs are placed on a Si substrate directly and no normal metal for a resistance is used. The peripheral chips on the active interposer consist of planarized four Nb layers, a Pd resister layer, Nb/AlOx/Nb JJs and TSVs for I/O paths.

This presentation is based on results obtained from a project commissioned by the New Energy and Industrial Technology Development Organization (NEDO).

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- Fabrication of superconductor sensors that exhibit high sensitivity and fast response.
- Large format arrays that sense soft X-rays and particles, and infrared photon-number resolving detectors have been realized.
- Measurement instruments that incorporate superconducting sensors exhibit superior performance over instruments that use conventional sensors.

Superconducting sensors

Superconductors enable the fabrication of sensors with high sensitivity (low noise) and fast response times. Superconducting sensors for γ-rays, soft X-rays, particles, and infrared photons exhibit superior performance over conventional sensors and are used in advanced measurement apparatuses, quantum information experiments and related areas. Superconducting sensors that exhibit superior performances can now be commonly used because it is possible to realize temperatures below 1 K.

Activities

- **4000-pixel Nb/Al STJ array for soft X-ray detection**
  A 100-4000 pixel Nb/Al STJ array realized a large active area of 1-40 mm² and high energy resolution of 4.1 eV @ 400 eV, simultaneously (Fig. 1), which is used for Superconducting fluorescence-yield X-ray absorption fine structure apparatus (SC-XAFS) and SEM-EDX analyzer utilizing STJs (SC-SEM). (Fig. 2) XAFS spectra of trace light elements in matrices can be obtained.

- **Superconducting strip ion detector (SSID) for TOF-MS**
  An SSID can detect particles with a high detection efficiency (100%) and fast response time (< 1 ns). Large area SSIDs (1 mm²) can be fabricated and used in MALDI-MS and ESI-MS. Mass spectrometers containing SSIDs can measure the charge separation of diatomic molecules and detect large biological molecules with high efficiency (Fig. 3).

- **Transition edge sensor (TES) for quantum information**
  A TES with an absorption structure for the communication wavelength band (1550 nm) achieved a high system detection efficiency of 98.4% (Fig. 4) and was used as a photon-number resolving detector for quantum information experiments.

New technologies

To improve the performance of superconducting sensors, a number of new technologies have been developed, including: (1) an STJ with a 3D-wiring structure for a large array format (> 1000 pixels), (2) an STJ with a bulk absorber for high absorption efficiency of X-rays less than 10 keV, (3) a combination of an SFQ-TDC and an SSID for MS with ultra mass resolution and (4) a TES array for a high throughput quantum communication.

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Fig. 1. Nb/Al STJ arrays for soft X-ray detection (< 2 keV) (A) 100 pixels, (B) 4096 pixels.

Fig. 2. Advanced measurement apparatuses (A) SC-XAFS (B) SC-SEM

Fig. 3. A superconducting strip ion detector (SSID) for a TOF-MS and an MS.

Fig. 4. A transition edge sensor (TES) with an absorption structure for the communication wavelength band (1550 nm).
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- Accurate and low noise operation that exceeds those of alternative devices (Semiconductors etc.).
- Development of key devices for next generation National Standards (NS).
- Introducing accuracy comparable to NS into industry and technology institutes.

Josephson Voltage Standards
Reliability is critical in measurement and metrology. We have developed and demonstrated highly accurate and low noise superconducting devices. We have realized compact, easy-to-use, and liquid-helium-free standards by developing the entire system with the superconducting devices as the key element. Our technology contributes to metrology improvements required for industrial growth.

Activity
We have developed niobium-nitride (NbN)-based voltage standard chips that exhibited stable operation at 12 K when supplied by a compact cryocooler. Secondary DC voltage standards with higher accuracy and stability than zener-dioded-based standards can be achieved by packaging a chip, cryocooler, and external circuits into a frame fitted into a 19-inch rack. Furthermore, we plan to regularly supply 10 V chips that only a few institutes in the world can currently fabricate. In addition to DC voltage standards, we are studying arbitrary waveform generators applicable for quantum AC voltage standards and Johnson noise thermometry.

Future Plans
- **Rack-mountable voltage standards**
  Chip: Delivery based on distributed system in NMIJ.
- **Liquid-helium-free 10 V DC voltage standards**
  Chip: Developing fabrication processes with higher yield.
  System: Achieved delivery to Japan, Australia, & Indonesia.
- **Arbitrary Waveform Generators**
  Currently being investigated for increasing voltage & accuracy.

Multiplexers for Readout of Superconducting Detector Arrays (SDA)
Reducing the heat-flow from 300 K to cryogenic temperatures in devices with increased pixel numbers is important for applying SDA to X-ray analysis, nuclear safeguards, astronomical observations, passive spectroscopic Terahertz imaging, etc. We are studying microwave frequency-division multiplexers for 10^2-10^3 pixels, which can process signals from the whole pixels using only two coaxial cables with the same signal-to-noise ratio as a single pixel readout. Low-noise operation of Nb SQUID and NbN resonators was successfully demonstrated.

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