EDP1-1

Neuro-inspired Quantum Associative Memory Model

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It is widely known that adiabatic Hamiltonian evolution algorithm [1] (including quantum annealing [2]) can solve combinatorial optimization problems. To enhance the versatility of its application, we have investigated the fusion of quantum and neural computing, because neural computing has succeeded to acquire algorithms automatically. As a first step of implementing learning function on quantum computers, we have proposed a neuro-inspired quantum associative memory (NQuAM) model [3] with a quantum neural network (QNN) which is composed of multiple qubits regarded as neurons. The memorization of the NQuAM is realized with a Hamiltonian derived from qubit-qubit interactions converted from neuron-neuron interactions of a conventional neural network. Then the adiabatic Hamiltonian evolution is performed to retrieve memorized patterns. A conventional neural associative memory converges to a certain state corresponding to one of the memorized patterns according to an initial state given as a key input. On the other hand, the NQuAM state is given as a superposition of all memorized patterns and does not converge to a specific state unless some additional treatment is applied. Therefore, we apply an external Hamiltonian $H_{\rm fix}$ to fix the state of some qubits, which imitates the role of a key input for a neural associative memory. Figure 1 shows the average retrieval probabilities $<P_{\rm ret}>$s of the 4-qubit NQuAM, where $A_{\rm fix}$ denotes an amplitude of $H_{\rm fix}$. Thus, the effectiveness of $H_{\rm fix}$ is confirmed. The memory capacity $M_{\rm cap}$ of the NQuAM is estimated as 2^{N-1}, where N is the number of qubits. Because $M_{\rm cap}$ of a conventional neural network is order of N, the large memory capacity of the NQuAM would be a big advantage. To receive the profit of the NQuAM model, it is necessary to investigate its hardware implementation. In this report, it will be discussed how to realize the NQuAM hardware with superconducting devices.

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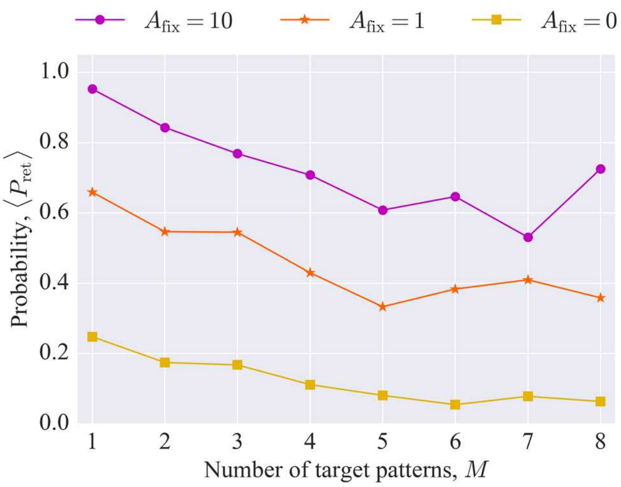
[2] T. Kadowaki and H. Nishimori, "Quantum annealing in the transverse ising model," Phys. Rev. E, 1998.
[3] Y. Osakabe et al., "Quantum associative memory with wuantum neural network via adiabatic Hamiltonian evolution," IEICE Trans. Inf. & Syst., 2017 (accepted, in press.)



Keywords: quantum computing, associative memory, quantum neural network

EDP1-2

Double-Flux-Quantum Amplifier with a Single-Flux-Biasing Line

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A Double-Flux-Quantum (DFQ) amplifier multiplies its input voltage with quantum accuracy by use of DFQ generation at under-damped junctions [1]. We conducted research on digital-to-analog converters implemented with DFQ amplifiers for metrological applications. Conventional DFQ amplifiers were usually operated with two flux-biasing lines. In this research, we redesigned the circuit layout to realize operation with a single flux-biasing line.
The equivalent circuit of the redesigned basic cell is shown in Fig. (a). Our previous work related to the reduction of flux-biasing lines suggested the new parameter set of a DFQ amplifier [2], although we demonstrated its operation partially. So we refined the equivalent circuit as shown in Fig. (a), where the inductance L_4 was introduced. We designed a new layout of a 20-fold DFQ amplifier and fabricated it using the Nb STP2 of the National Institute of Advanced Industrial Science and Technology.
The measurement was performed in liquid He. The SFQ pulse train was fed by the over bias method, and the input-output characteristics were measured with an oscilloscope (Fig. (b)). When the magnetic flux bias current $I_{\rm fb1}$ was not applied, the maximum input voltage $V_{\rm inmax}$ was 68 V (red), which was about 4.2 times larger than that of 16 V (blue) of $V_{\rm inmax}$ of the previous study [2]. $V_{\rm inmax}$ was enhanced to 120 V with $I_{\rm fb1}$ of 1.00 mA (purple).

[1] Q. P. Herr, IEEE Trans. Appl. Supercond. **15** (2005) 259.
[2] Y. Mizugaki et al, IEEE Trans. Appl. Supercond. **26** (2016) 1301104

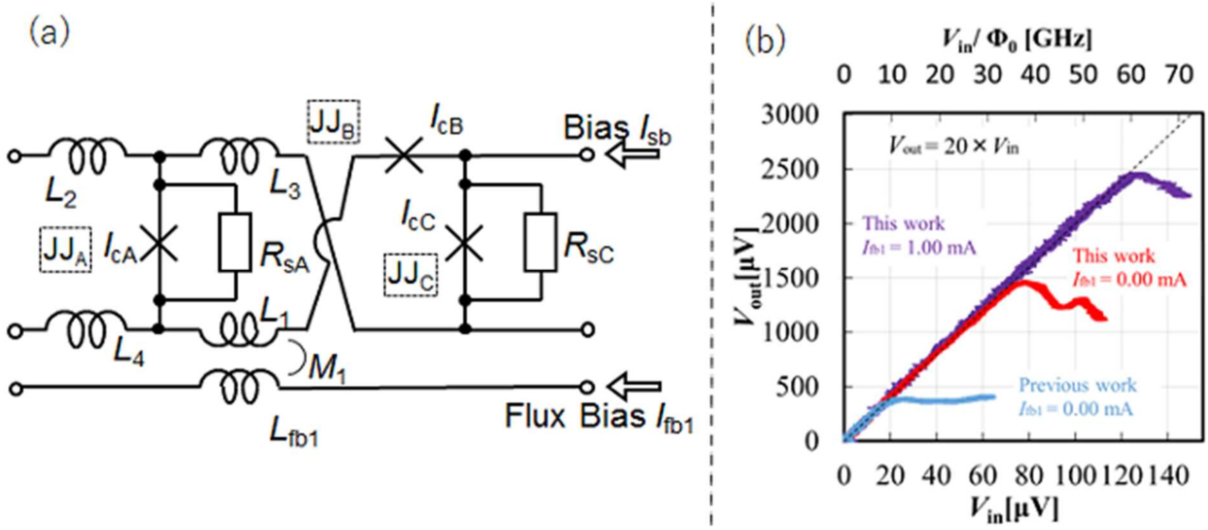

Fig. (a) DFQA of the basic cell; 3 Junctions Loop, (b) Input-Output(*Vin-Vout*) characteristics demonstrating 20-folds voltage multiplication

Keywords: Double-Flux-Quantum Amplifier, Quantum voltage multiplication, Nb integrated circuits
210025

EDP1-3

A random-access-memory cell based on quantum flux parametron with three control lines

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Adiabatic quantum-flux-parametron (AQFP) logic has a potential to become a basic technology to realize an ultra-low-power computing system because of its extremely low bit-energy with three orders of magnitudes lower than that of rapid single-flux-quantum logic [1]. Although large-scale random-access memories (RAMs) are needed for realizing high-performance computing systems, any RAMs compatible with AQFP have not been studied yet. In this study, we have proposed a RAM cell composed of quantum-flux-parametron (QFP) circuits as a component of a large-scale AQFP RAM. The memory cell is composed of a storage QFP gate and a read AQFP gate. The memory cell in our previous study needs three control currents for writing and two control currents for reading, This time, we have proposed a new random access memory cell controlled by three control currents (I_d, I_y, I_x), where I_d corresponds to the input datum, I_y is the column selection current for writing and I_x is the row selection current for both writing and reading. The number of control lines has been decreased by reading memory cells in the same row at the same time and by using common word line for both writing and reading. We have optimized the circuit parameters of the memory cell to increase the bias current margins using the Josephson circuit simulator (JSIM). The evaluated control current margins are larger than +/- 30%. The cell size is estimated to be 50 mm x 40 mm, which can be further decreased by using multi-metal-layer processes. Cell test results will be shown in the presentation.
[1] N. Takeuchi, K. Ehara, K. Inoue, Y. Yamanashi, and N. Yoshikawa, *IEEE Trans. Appl. Supercond.*, vol. 23, no. 3, p. 1700304, Jun. 2013.

Keywords: QFP, AQFP, memory, Josephson integrated circuits

EDP1-4

Proposal of superconducting analog to digital converter using quantum flux parametron

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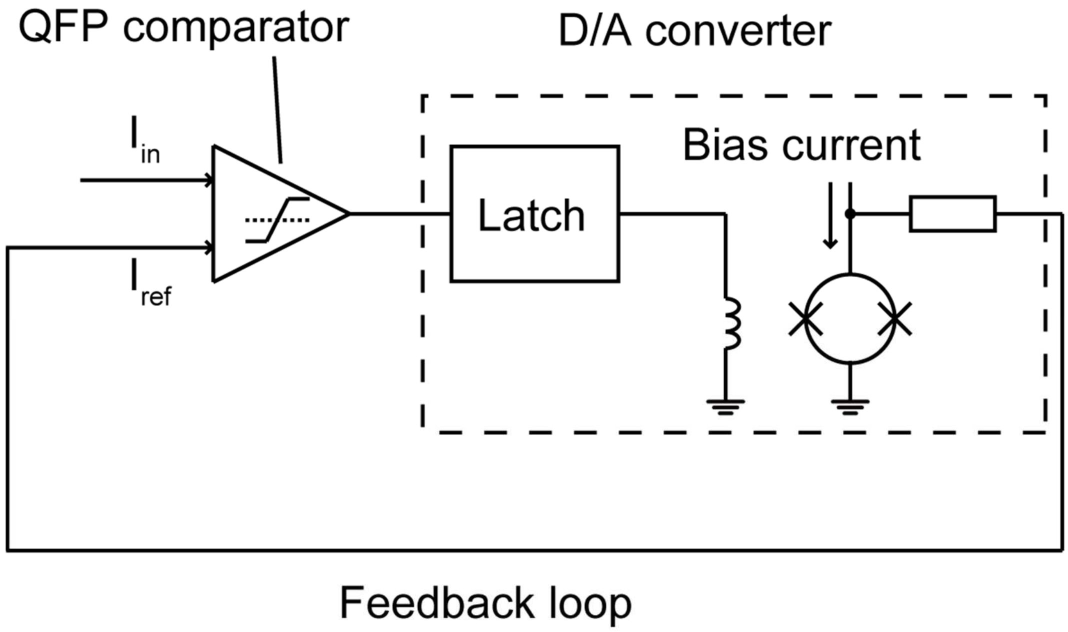
Various superconducting analog to digital converters (ADCs) that have the ultra-high sampling rate have been studied [1]. Because those superconducting ADCs use internal magnetic feedback when one single-flux-quantum (SFQ) signal is output, the input magnetic signal resolution is limited to be one magnetic flux quantum in superconductors. In this study, we propose a superconducting ADC that has better signal resolution than that of ADCs proposed so far by utilizing quantum flux parametron (QFP) [2] as the signal detection circuit. Because magnetic flux resolution of the QFP is less than 1/100 of magnetic flux quantum at the sampling frequency of 1 GHz [3], the input resolution of the ADC can be improved compared to conventional superconducting ADCs. Figure shows a block diagram of the proposed superconducting 1-bit ADC that employs the successive approximation method. By comparing the input signal (I_{in}) and the reference signal (I_{ref}) by the QFP comparator, the input signal is quantized. The reference signal is generated by the digital to analog converter composed of the quantum flux latch (QFL) [4] that stores comparing results output from the QFP comparator. By connecting the circuit shown in the figure in series, the *n*-bit successive approximation ADC can be built. We simulated and confirmed correct operation of the proposed ADC. Performances of the ADCs such as the minimum quantization level and the maximum sampling frequency are investigated on the basis of theoretical analysis and the circuit simulation.



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Keywords: Quantum flux parametron, ADC, comparator, high sensitivity

EDP1-5

Study on Integer-Number Parallel Divider Based on Single Flux Quantum Logic

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Division is one of important arithmetic instructions in the computation systems. Especially, division is frequently used for the scientific application. Among the arithmetic operations, division is one of the most complex calculations in the computation systems. If division is calculated by a general-purpose arithmetic logic unit (ALU), that results in long calculation time. This is thought to be serious problem for single-flux-quantum (SFQ) digital processor [1] that usually employs bit-serial processing.

In this study, we investigated and designed an integer-number SFQ divider based on bit-parallel and bit-slice architectures [2]. Fig. 1 shows a block diagram of the SFQ *n*-bit parallel divider based on a non-restoring division algorithm. We designed the parallel divider using the AIST 10 kA/cm^2 Nb advanced process [3]. Logic simulation results indicate the maximum operating frequency is 77.5 GHz. The bias margin at the target frequency of 50 GHz is 80%–125%. Details of the circuit design and experimental results will be presented at the conference.

Acknowledgement

In this work, the CONNECT ADP cell library and tools were used in this study. The circuits were fabricated in the clean room for analog-digital superconductivity (CRAVITY) at AIST with the advanced process 2 (ADP2).

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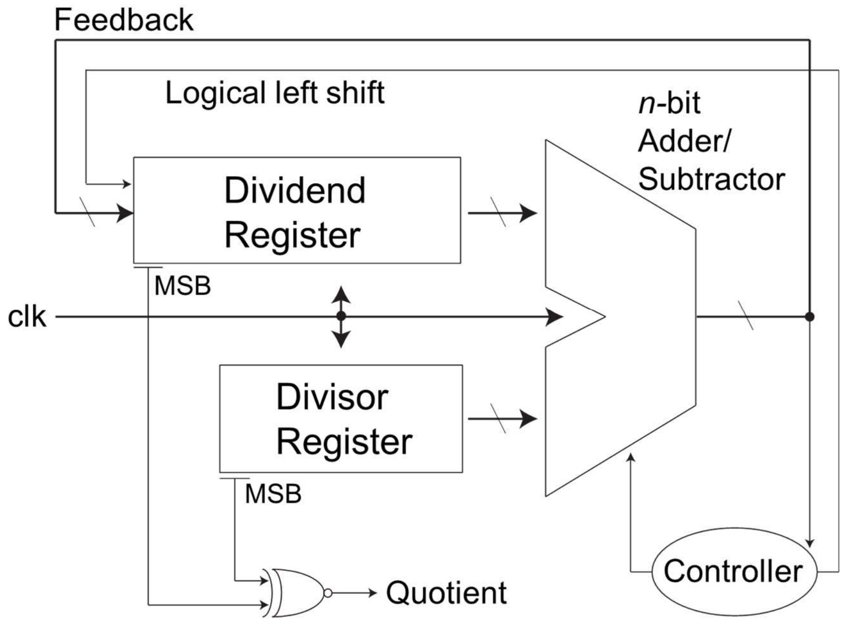
[2] M. Hidaka, et al., Supercond. Sci. Technol., vol. E91-C, pp. 318-324, 2008.
[3] G. M. Tang, et al., IEEE Trans. Appl. Supercond., vol. 27, p. 1301005, 2017.



Keywords: Single flux quantum logic, Superconducting integrated circuits, Divider

EDP1-6

Design of an arithmetic logic unit and a data shifter for adiabatic quantum-flux-parametron-based microprocessor

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Adiabatic quantum-flux-parametron (AQFP) logic is an emerging technology in superconducting electronics that shows promise towards building extremely energy efficient computing systems with bit energies approaching $100k_BT$ and has already demonstrated circuits consisting of more than 1000 Josephson junctions. In the effort of building an AQFP-based microprocessor, we have designed two key datapath units using a 4-phase AQFP logic library: a 4-bit arithmetic logic unit (ALU), and a 4-bit data shifter.
The ALU is based-on the Kogge-Stone prefix-adder structure and supports arithmetic addition and subtraction operations, as well as logical operations, namely: AND, OR, XOR and XNOR. It was designed based on a semi-custom approach where sub-blocks were designed by hand using the logic cell library. Sub-blocks were then arranged together into logical rows. The 4-phase bias connections consisting of 2 ac lines and 1 dc line were automatically generated from our AQFP electronic design automation (EDA) toolchain. The logical wiring between gates were completed in a similar way.
The data shifter has been completely synthesized using our EDA toolchain based on the open-source 'yosys' logic synthesis tool with an AQFP cell mapping file. This combinational data shifter supports left/right logical shift, and arithmetic right shift operations.
Both datapath units have been designed using the AIST 10 kA/cm^2 high-speed standard process (HSTP) and have been simulated using the clock-skew aware SystemVerilog models included in our cell library. It is expected that these units can operate at 5 GHz, the clock rate target of our AQFP microprocessor. The ALU and data shifter consists of 1058 and 498 Josephson junctions, and have a latency of 5 cycles (20 phases), and 2.5 cycles (10 phases) respectively.

Acknowledgment
This work was supported by a Grant-in-Aid for Scientific Research (S) (No. 26220904) from the Japan Society for the Promotion of Science (JSPS). This work is also supported by VLSI Design and Education Center (VDEC), the University of Tokyo in collaboration with Cadence Design Systems, Inc.

EDP1-7

Development of the Large-scale Superconducting Nanowire Single-photon Detector Imaging Array

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Development of a large-scale Superconducting nanowire single-photon detector (SSPD or SNSPD) imaging system has recently attracted attention. Since the SSPD has excellent characteristics such as high system detection efficiency, low dark count rate, and superior timing resolution, it has been applied in various research fields. In addition to these excellent characteristics, the SSPD imaging system has the feature that it is possible to identify photon detection positions with high detection timing resolution. This unique feature has the potentiality of application to a wide range of fields such as biological imaging, laser imaging detection and ranging (LIDAR), spectroscopic measurement, quantum imaging and so on.
A major issue in the development of the large-scale SSPD imaging system is heat inflow through enormous readout lines. To overcome this heat inflow problem, we are developing the large-scale SSPD imaging system with two readout multiplexing technologies. The first one is a new multiplexed readout architecture for a SSPD imaging array which recently demonstrated by the NIST group [1]. This architecture remarkably reduces the number of wiring lines required for the N x N array to 2N from N^2. The second technology is readout multiplexing using cryogenic signal processors based on single-flux-quantum (SFQ) circuits. We already demonstrated a 64-channel event-driven serial encoder composed of the SFQ circuit, which for a 64-pixel SSPD imaging array with conventional one-to-one readout architecture. By improving this encoder for the new readout architecture, it becomes possible to readout information of detection position and detection time from the 32 x 32 = 1024-pixel imaging array via only two serial lines.
In the presentation, we report fabrication of a 1024-pixel SSPD imaging array with above new readout architecture. We also report the results of evaluating its superconducting and photo responsive properties.

[1] M. S. Allman et al., Appl. Phys. Lett., 106, 192601 (2015).

Keywords: Single-photon detector, Nanowire, Imaging array, SSPD

EDP1-8

Study on Multipoint Guided Wave Measurement Technique on Pipes using HTS-SQUID NDI System

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This paper describes study on multipoint ultrasonic guided wave measurement technique on pipes using HTS-SQUID nondestructive inspection (NDI) technique. The HTS-SQUID NDI system based on T (0, 1) mode ultrasonic guided wave utilizing magnetostrictive effects and a HTS-SQUID gradiometer was used. To generate the guided waves using the magnetostrictive effects, thin nickel board were magnetized using a solenoid coil. By changing a current amplitude supplied to the coil, magnetization fields to the nickel board inside the coil were changed. Distribution of leakage fields around the magnetized nickel boards were measured using a Hall sensor. We found that the leakage field at 12 mT were more uniform than that at 6 mT, which affects the performance of the HTS-SQUID gradiometer, which is set near the magnetized nickel board to measure magnetic signals from the nickel board based on the magnetostrictive effects. The maximum amplitude of the magnetized field from the nickels board magnetized at different magnetization fields did not differ significantly. Finally, the nickel boards magnetized at 12 mT was firmly adhered around circumferences of a sample aluminum pipe, and multipoint guided wave measurement around the pipe was carried out using the NDI system. While supplying a burst sine wave current of one cycle with 1 A_{pp} at 60 kHz into a field coil wound around the nickel board, distribution of the magnetic signals due to generated guided waves on the pipes around the circumference of the pipe was successfully measured.

Keywords: HTS-SQUID gradiometer, guided wave, pipe, multipoint measurement

EDP1-9

Ultra Low Field SQUID-MRI using Non-Resonant Cu Wound Flux Transformer

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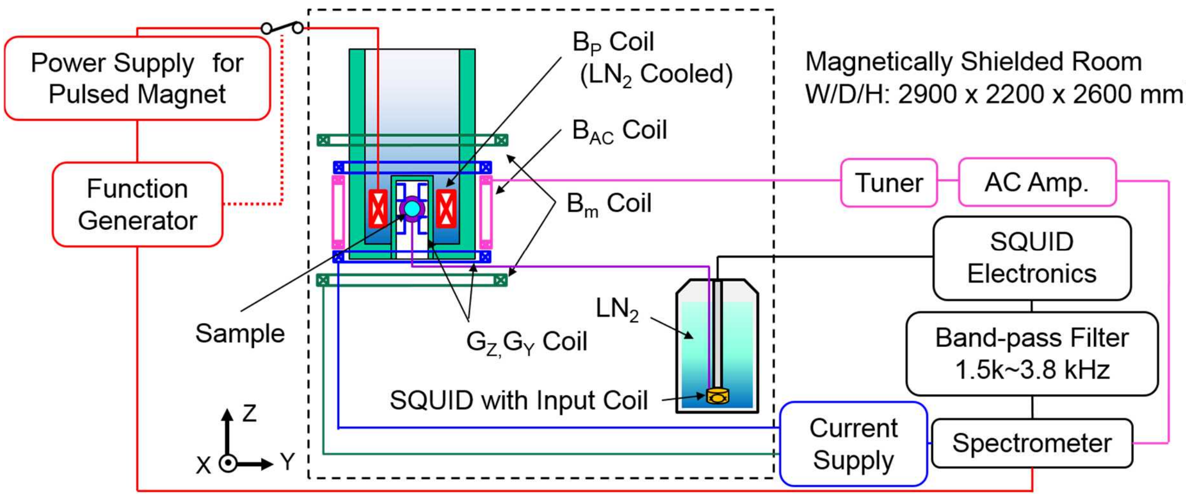
We are developing an Ultra Low Field (ULF) Magnetic Resonance Imaging (MRI) system with high-temperature superconductor superconducting quantum interference device (HTS-SQUID) for the purpose of food contaminant inspection. The new system using the ULF SQUID-MRI technique has the potential to detect not only a metallic but non-metallic contaminants. Since our previous ULF SQUID-MRI system for food inspection used a resonant circuit to detect a magnetic field, which was tuned at Larmor frequency. However, a Q value of the resonant circuit corresponding to the sensitivity became poor with decrease of the frequency of MR signals. In order to increase the Q value, it is necessary to elongate the signal acquisition time, which corresponds to a reciprocal number of the bandwidth. Therefore, it is difficult to measure the MR signal of food with short relaxation time, such as fat, because of the longer acquisition time.
In this paper, we will describe a ULF SQUID-MRI system using a non-resonant Cu wound flux transformer to measure fat of which relaxation time is shorter. Fig.1 shows a schematic of the ULF SQUID-MRI system. The main system consists of the following units: An HTS dc-SQUID with flux transformer, a Helmholtz type measurement field (B_m) coil, an AC pulse (B_{AC}) coil, two sets of gradient field coils (G_x, G_z), a polarizing field (B_P) coil and an NMR spectrometer (Kea[2], *Magritek*, New Zealand). The flux transformer consists of a pickup coil at room temperature and a flip chip type input coil integrated with the SQUID.
The MR image of food contaminant sample will be discussed on the day.



Keywords: HTS-SQUID, ULF-MRI, Food inspection, Flux Transformer

EDP1-10

Constructing a Vector Scanning SQUID System

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Superconducting quantum interference device (SQUID) is a fundamental sensor in constructing an ultrasensitive magnetic measurement equipment. In many preceding cases, it is supposed to be impossible to build such a highly sensitive instrument except for SQUID. Therefore, the SQUID devices are employed in various fields such as magnetics, electronics, biology, spintronics, security analysis, agriculture, information technology, communication, material science, and physics [1]–[3]. However, a typical scanning SQUID microscope has a single pick-up coil and a single channel SQUID readout circuit to obtain the distribution of local magnetic field component only perpendicular to the sample surface along the Z direction. Recently, we started to develop a scanning SQUID vector microscope equipped with a vector pickup coil (Fig. 1), which intends to achieve high sensitivity in the magnetic field and high spatial resolution in vector field mapping [4], [5]. We placed the positions of X, Y and Z coils to keep the same heights to sample and the distance of center coils to each other in integer of scanning step to make a convenience in synthesizing a vector magnetic field (Fig.1(b)). The new sensors have improved the sensitivity by utilizing multiple windings of the pick-up coil with the aid of multi-layer fabrication process of the superconductive foundry CRAVITY of AIST. Scanning vector SQUID microscopy is under construction by using a 3-channel SQUID readout circuit (Magnicon Inc.), an 3-channel XYZ piezo-driven scanner (Attocube Inc.), and a Gifford-McMahon cryocooler (Sumitomo Inc.). We confirmed that the voltage outputs from the SQUID readout circuit are in good agreement with the profile of the output (*V*-F) characteristics of the SQUID sensor. The first images of a vortex in a $Mo_{80}Ge_{20}$ thin film were obtained successfully by using our own SQUID sensor in our existing SQUID microscope.

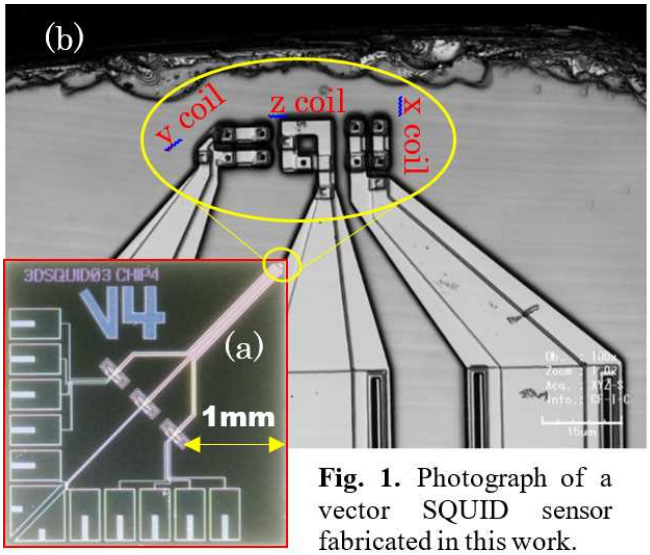

Fig. 1. Photograph of a vector SQUID sensor fabricated in this work.

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Keywords: SQUID microscopy, Vector sensor, Scanning microscope, , 3D sensor

EDP1-11

Precision measurements of transuranium elements using superconducting transition edge sensor

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Nondestructive analysis using gamma-ray and x-ray emitted from radioactive elements is used in a various field such as nuclear transmutation and nuclear activation analysis. In this field, scintillation detectors or high-purity Germanium detectors are used for measuring gamma-ray or x-ray but they are difficult to identify or detect nuclides since the energies of photons emitted by transuranium elements such as Plutonium and Americium are close to each other or gamma-ray or x-ray emitted by nuclides are covered with Compton scattering.
To solve this problem, we focused on the superconducting transition edge sensor (TES) which is an exquisitely sensitive device exploiting the abrupt change in resistance at the onset of the superconducting transition and selectable gamma-ray or x-ray absorber made by high Z material. Therefore, in order to demonstrate the precision measurement of nuclear material samples using a TES microcalorimeter, we have designed and fabricated a gamma-ray TES spectrometer for nuclear material analysis which is Ir/Au-TES and coupled to a tin radiation absorber by using a gold bump post.
In this presentation, we will report the results of irradiated and non-irradiated Np samples by using TES microcalorimeter and we consider that gamma-ray spectrometer using a TES microcalorimeter can be applied to the advanced non-destructed inspection of the nuclide material.

Keywords: superconducting transition edge sensor, Neptunium samples

EDP1-12

Study on Lumped Element Kinetic Inductance Detectors for Light Dark Matter Searches Using Liquid Helium

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We have developed the superconducting detector LEKID (Lumped Element Kinetic Inductance Detectors) for a dark matter search using liquid helium. It is supposed that the dark matter consists of weakly interacting massive particles (WIMPs). Direct searches for the WIMPs have been conducted using Xe, Ge, Si and NaI as targets. Those experiments have sensitivities for WIMP mass down to about 10 GeV/c^2. In 2013, W. Guo and D. N. McKinsey have proposed to use liquid helium as a target to obtain a sensitivity beyond 10 GeV/c^2 in WIMP mass. Helium may have sensitivity to the light WIMP mass less than 10 GeV/c^2, as it is a light element. Recoiled helium atoms produce scintillation light photons with the wavelength of 80 nm (16 eV in energy). Those photons are detected with the superconducting detector LEKID. The LEKIDs offer us a frequency domain multiplexing readout that reduces the number of readout cables, decreasing the heat load from the outside.

The superconducting detectors are fabricated with photolithographic techniques in clean rooms, CRAVITY at AIST and one at KEK. We use Nb or NbN for superconducting materials. The sensitivity of LEKIDs can be estimated by the phase responsivity. We measured temperature dependency of performance of LEKIDs to calculate the phase responsivity. And we measured response of LEKIDs by the visible lights. We report on the current status of the development of LEKIDs that satisfy our requirements.

Keywords: Kinetic Inductance Detectors, Dark matter

EDP1-13

Flip-chip bonding technology for high performance STJ array detector using superconducting bumps

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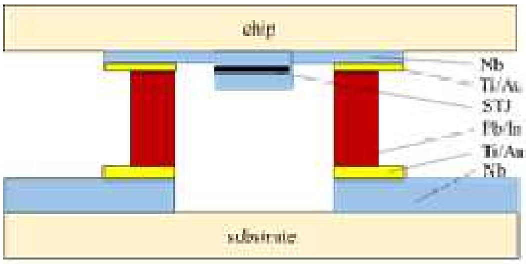
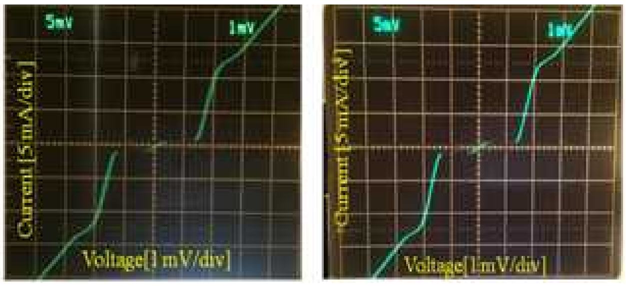
Superconducting tunnel junction (STJ) is one of the candidates as a next generation photon detector because of high energy resolution and wide bandwidth. In order to obtain a two-dimensional image of detected photons, it is necessary to array a large number of STJs on a chip. The integration density of STJs is limited by the wiring area when the STJ-array is enlarged. To solve this problem, we have proposed an "embedded STJ" (e-STJ) with a three-dimensional packaging structure [1].
In this research, we focus on flip-chip bonding (FCB) connection as a three-dimensional mounting method. To obtain high quality detected signal transmission superconducting Pb / In alloy bumps are introduced in the three-dimensional packaging structure. And we have been evaluated the FCB conditions and the electrical characteristics of the bumps.
Fig. 1 shows the schematiccross-sectional view of the sample used in this work. The STJ of upper chip is FCB connected by the Pb / In alloy bumps made on the substrate. The electrical characteristics of the STJ were measured at 4.2K through the superconducting bumps before and after the FCB as shown in Fig.2. The superconducting FCB connection is successfully demonstrated in the three-dimensional packaging structure. The details will be presented.





Keywords: superconducting tunnel junctions, flip-chip bonding, bump

EDP1-14

Development and evaluation of Multi-Layer Superconducting detectors for the CMB polarization observation

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The Big Bang cosmology is a prevailing theory to describe the early universe. It also has outstanding problems such as the flatness problem, the horizon problem and the magnetic monopole problem. The cosmic inflation, exponential expansion of the space, gives an initial condition of the Big Bang to resolve these problems. The inflation theory predicts the existence of primordial gravitational waves(PGWs). The PGWs produce specific polarization patterns (B-modes) on the Cosmic Microwave Background(CMB). B-modes are the direct evidence of inflation [1].
GroundBIRD aims to search for B-modes from the ground. It employs a large-scale array detector of Kinetic Inductance Detectors(KIDs) [2]. The observing frequencies are 145 GHz for the CMB observation as well as 220 GHz for dust foreground subtraction. The sensitivity of the single KIDs required to be the photon noise limited level under the operation temperature of 250 mK and the loading from the sky of Canary Islands.
We investigated the performance of KIDs which employed multilayer of titanium and titanium nitride (TiN). TiN KIDs have a higher responsivity compared to Al KIDs. The critical temperature T_c of TiN/Ti multilayer can be precisely controlled from 1 K to 4 K with excellent uniformity in 3-inch wafer [3]. From BCS theory, the relation between superconducting energy gap and T_c is described to be $\Delta=3.52k_BT_c/2$. Strictly speaking, the relation depends on the material of superconductor. We investigated it in case of TiN/Ti multilayer. We also optimized the T_c by the tuning to the thickness of titanium for the environment of scientific observations. We fabricated 14 TiN/Ti KIDs (T_c =1.72 K) as shown in Fig. 1. The range of resonance frequencies of the KIDs is 3.45 GHz to 3.55 GHz. We measured optical response of these KIDs. The detail results will be presented.

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