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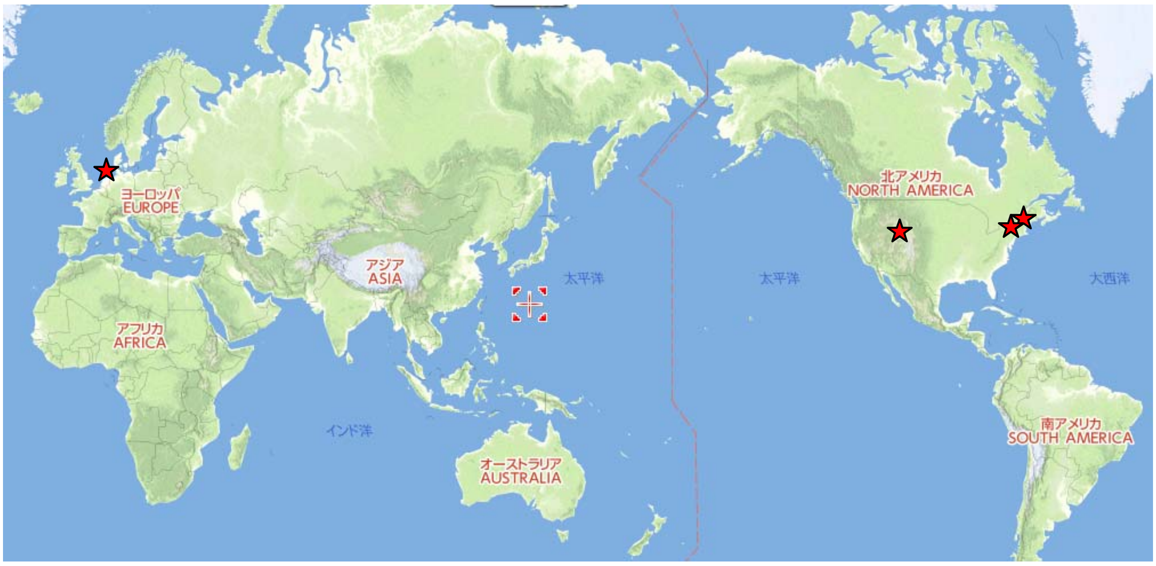
What's New in the World of Superconductivity

초전도 뉴스 –세계의 동향–

超导新闻 –世界的动向-

chāo dǎo xīnwén - shìjiè de dòngxiàng-

Yutaka Yamada, Principal Research Fellow
Superconductivity Research Laboratory, ISTEC



★News sources and related areas in this issue

▸Wire 선 재료 线材料 [xiàn cáiliào]

Mechanical Test Facilities for Customer

SuperPower (26 Jan, 2015)

SuperPower Inc. has announced the start of its own dedicated facilities for the testing of mechanical/electromechanical properties of its 2G HTS wires. The superconducting characteristics of such HTS wires are affected by the applied stresses/strains, and thus a better understanding is very important in the design, fabrication and operation of HTS devices. It is therefore anticipated that these facilities will ensure a continuous and robust improvement in the performance characteristics of its 2G HTS products. SuperPower is also closely working with the IEC/TC90 to ensure the testing methods employed conform to the applicable standards. The data from these tests will be provided to its customers to support their applications.

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Specifically, the completion of a recent project has enabled Superpower to have the capabilities to undertake mechanical/electromechanical tests in liquid nitrogen and also measure critical currents under either longitudinal or transverse tensile stress conditions. Additional to anvil tensile tests, pin-pull and peel tests are also being employed to investigate the mechanical behaviors of the wires under a transverse tensile stress. Currently, SuperPower is working on setting up for compressive testing and twist testing, and thus their commitment to mechanical/electromechanical testing capabilities continues.

Source:"Superpower has established comprehensive testing capabilities for the assurance of the mechanical/electromechanical performance of its 2G HTS wires"
(26 Jan, 2015) News Release
http://www.superpower-inc.com/content/superpower-establishes-comprehensive-testing-capabilities-assurance-mechanicalelectromechani
Contact: Mickey Lavicska mlavicska@superpower-inc.com

▸Electronics 엘렉트로닉스 电子应用［diànzǐyè yìngyòng]

Nano-memory for Superconducting Computer

NIST (23 Jan, 2015)

The growing demands of cloud computing in recent years have prompted the creation of centralized computing facilities at sites around the world. Such facilities operate 24 hours per day and utilize semiconductor-based electronics, which are typically power hungry and generate substantial amounts of heat that also needs energy to remove.

A promising replacement technology is superconducting (SC) computers, employing instead, Josephson junctions (JJs) that dissipate small amounts of energy and can operate at gigahertz frequencies, compared to a few gigahertz for semiconductor computers. Recent research work has led The Intelligence Advanced Research Projects Activity (IARPA) to ascertain that major breakthroughs are forthcoming and has launched a multi-year program to investigate the practical viability of SC computing.

For the IARPA program, NIST scientists have developed and demonstrated a new nanoscale memory technology for superconducting computers that functions at cryogenic temperatures, utilizing the fast switching speeds of JJs thus offering the potential of low-energy computing. The NIST team's module is the first to employ spintronic effects, which are acutely difficult to characterize on the nanoscale. Their memory module, described in a 2014 publication, is a modified JJ, 100 nanometers thick comprising a multi-layer barrier consisting of two different magnetic materials separated by a non-magnetic metal. The behaviors of different barrier configurations and materials for use in memory are now being investigated.

"The combination of low-loss superconducting logic and nonvolatile, hybrid magnetic memory could revolutionize mainframe computation and data storage within a decade," says Ron Goldfarb, leader of the NIST Magnetics Group and a supporting member of the NIST team.

Source:" Hybrid memory device for superconducting computing"
(23 Jan, 2015) News/Multimedia
http://www.nist.gov/pml/electromagnetics/magnetics/hybrid-memory-device-for-superconducting-computing.cfm
Contact: Burm Baek burm.baek@nist.gov

▸Basics 기초 基础[jīchǔ]

Superconducting Nano-wire

University of Copenhagen (12 Jan, 2015)

Researchers at the University of Copenhagen are behind the breakthrough of a new type of 'nanowire' crystal based on aluminium, which can fuse semiconducting and metallic materials on the atomic scale. Their work appears in Nature Materials, demonstrating a perfect contact and also showing that they can make a chip with billions of identical semiconductor-metal nanowire hybrids.

This new material comprises of both a semiconductor and metal, having superconducting characteristics at cryogenic temperatures. This hybrid material has great potential according to Associate Professor Thomas Sand Jespersen, who has worked in the field for more than 10 years, ever since research into nanowire crystals was launched at the Nano-Science Center at the Niels Bohr Institute. The challenges with nanowires have been in creating good electrical contacts to the outside world. Groups around the world have fabricated nanowires and contacts separately, however with the new approach, both the quality and the reproducibility of the contacts have improved significantly. Assistant Professor Peter Krogstrup explains that this opens many opportunities to make new types of electronic components on the nanoscale, leading to intensified studies about the electrical properties with much greater precision than ever before.

Source:" New superconducting hybrid crystals developed at the University of Copenhagen"
(12 Jan, 2015) News
http://www.nbi.ku.dk/english/news/news15/new-superconducting-hybrid-crystals-developed-at-the-university-of-copenhagen/
Contact: Peter Krogstrup krogstrup@nbi.ku.dk

HTS Fingerprint

Cornell University (6 Jan, 2015)

Scientists at Cornell have isolated the "fingerprint" which is believed pinpoints the specific fluctuations of electrons that force them into pairs, producing resistance-free superconductivity in "unconventional" superconductors. The group has proved that spin fluctuations are the cause of the electrons to form pairs.

In conventional superconductors, it is well understood that superconductivity occurs because electron pairing is driven by an exchange of lattice vibrations, which become strong enough to overcome Coulomb repulsion, but only at very low temperatures. However, the mechanism of superconductivity in "unconventional" superconductors has been a mystery. In such superconductors, the electrons tend to form antiferromagnets, and this tendency, prior to onset of the antiferromagnetic ordering, produces the spin fluctuations.

Associate professor of physics Eun-Ah Kim, explained that, "the fact that these spin fluctuations could provide electron pairing has been conjectured many times over, but proving it has been a big challenge and the methods that had worked for simple metals like aluminum don't quite work for higher temperature superconductors." A new class of iron-based unconventional superconductors, the so-called multiband systems, means that electrons at a given energy can have several different momentum states, each with different velocities. By employing an energy-momentum measurement technique called quasiparticle interference imaging, they successfully differentiated between the fingerprint due to spin fluctuations and lattice vibrations. Their findings are published online Dec.22 in Nature Physics, in an article entitled, "Identifying the 'Fingerprint' of Antiferromagnetic Spin Fluctuations in Iron Pnictide Superconductors".

Source:" High-temperature superconductor 'fingerprint' found"
(6 Jan, 2015) Cornell Chronicle
http://news.cornell.edu/stories/2015/01/high-temperature-superconductor-fingerprint-found
Contact: Anne Ju amj8@cornell.edu

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Feature Article: Cryogenic Digital Devices -The Effects of Magnetic Thin Films Employed in Superconducting Digital Circuits

Hiroyuki Akaike, Associate Professor
Graduate School of Engineering, Nagoya University

A particular characteristic of superconducting digital circuits including single flux quantum (SFQ) circuits is their low power operation. In recent years, this advantageous characteristic has gathered attention leading to buoyant R&D activities aimed at further low power operations. One of the targeted aims of superconducting digital circuits is the prospect of realizing energy-efficient high-performance computing systems. Therefore, they possibly offer the key in addressing the future issues associated with the vast amounts of power consumed by supercomputers and data center facilities. In fact, the development of an ultra-low power circuit and their systematization has been actively ongoing under the Cryogenic Computing Complexity (C3) program [1)] in the USA, and under the JST-ALCA project [2)] and Grant-in-Aid in Japan. In recent years, the introduction of magnetic materials into circuits or Josephson junctions in circuits has been studied in order to realize greater circuit performance and functionality. This article briefly highlights the advantages of magnetic thin films utilized in superconducting digital circuits including the trials undertaken by the author and his research team.

One of the most notable characteristics of magnetic materials is their magnetization. The switching of their magnetization used in for example, Magneto-resistive Random Access Memory (MRAM), is applicable to realization of high-capacity superconducting memory devices for practical use, because the utilization of the magnetization would lead to elimination of the conventional use of superconducting loops for storing flux quanta as a storage cell. The above-mentioned C3 program places the development of high-density cryogenic memory as an important factor that is driving R&D activities aimed at magnetic Josephson Junctions and superconducting MRAMs. The author's research team has commenced studies on magnetic Josephson Junctions, employing magnetic PdNi alloys as a junction barrier. Measured tolerance characteristics for potential integration have been proved as having a 0.7 % device-to-device variation (1σ standard deviation). Other advantageous characteristics afforded by magnetic materials used for circuits include the ability to bias their magnetic flux. In other words, a micro magnetic pattern incorporated into the circuit allows a magnetic flux to be induced locally.

The magnetic flux biasing is one of the methods that enhance the functionality of superconducting circuits that are constructed by parallel connection of SQUIDs, or superconducting loops containing Josephson Junctions. A superconducting loop within a circuit is now highlighted. The phase change in the microscopic wavefunction along a closed superconducting loop is equal to an integer multiple of 2π, based upon the quantization condition. With the application of an external magnetic flux to the loop, an additional phase difference is produced dependent upon the magnitude of the flux applied eventually shifting the phase modulation. Elements that induce additional phase difference are called superconducting phase shifters, and a variety of such elements have been proposed (Table 1).

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Table 1 A comparison between each type of superconducting phase shifter

Phase shifting element	Degree of shift	Characteristics	Issue/disadvantage	References
Flux-trap loop	π	Simple fabrication	Element size, Flux trap operation is required	3)
YBCO corner-SQUID	π	*d*-wave superconducting gap symmetry	HTS process, layout	4)
Ferromagnet-based Josephson π-junction	π	Process applicability, Small sized element	Control of element characteristics	5)
Magnetic-patterned	Discretional	Simple fabrication, Extremely small-sized element	Magnetization control, Flux leakage	Nagoya University

Significant advantages attained by utilizing phase shifters include reduced power consumption of circuits[4] and reliable circuit operation [6]. When a phase shifter is implemented in a SQUID loop, a circulating current naturally forms in the loop because of phase change of the superconducting macroscopic wavefunction. On the other hand, a circulating current in a conventional circuit is generated by applying a magnetic flux via mutual inductance or by supplying bias currents asymmetrically to the loop storing SFQ. Therefore, implementing a phase shifter into the loop in circuits can reduce the numbers of bias lines thereby reducing the total amount of bias current, further reducing power dissipation. Additionally, with improved operating margin and bit error rate further operational reliability can be achieved.

A phase shifter utilizing magnetic materials where the author's research team has been studying, offers advantageous characteristics to allow simple fabrication/down-scaling of elements, in addition exhibiting a great deal of flexibility in being able to specify phase shift changes. Magnetization control is inevitable for employing such phase shifters. The magnetic effects provided by the phase shifter have been studied up to now by using a single Josephson Junction or SQUID with magnetic patterns. An example is shown in Figure 1. When an external magnetic field is applied during the cooling-down process of the sample (field cooling), the effect of a magnetic flux biasing can be observed. The degree of flux bias is understood to be controllable by the strength of the magnetic field applied during field cooling. Currently, the advantages offered by a phase shifter implemented in a circuit (Figure 2) are being progressively investigated.

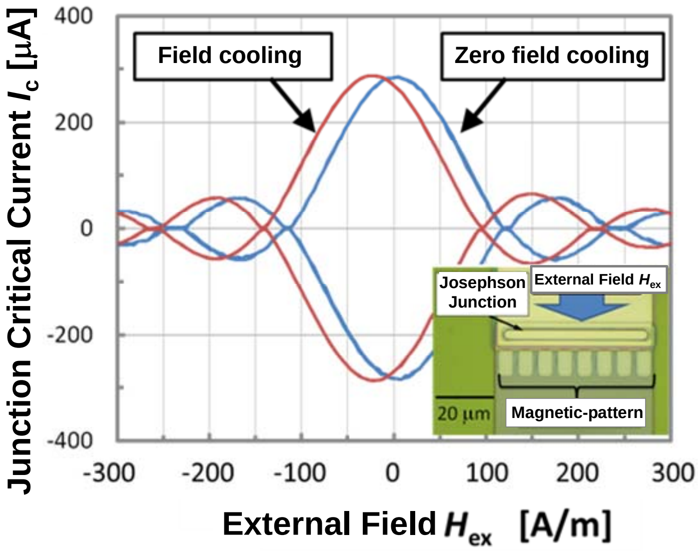

Fig. 1 Critical current of a Josephson Junction with a magnetic pattern as a function of the external field. A shift in the characteristics due to field cooling can be observed.

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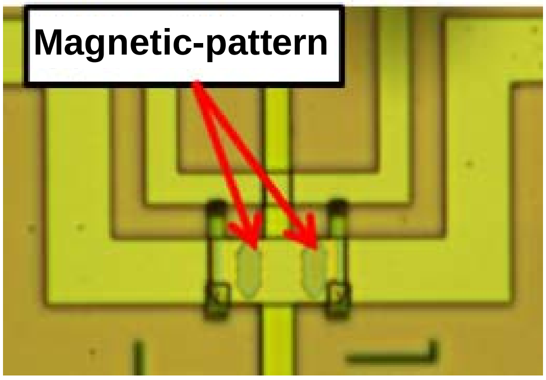

Fig. 2 Circuit with a Magnetic pattern

It is anticipated that the utilization of magnetic materials for applications ranging from junctions to circuits will allow further performance enhancements of superconducting digital circuits and offer significant progress in realizing a practical circuit. In order to accomplish such research and development it is desirable to include not only researchers specialized in the field of superconducting digital circuits, but also trans-disciplinary research groups, including those researchers specializing in the field of magnetic materials. The formation of such research taskforces has led to advancements as seen in typical examples of the C3 program. The launch of such a full-scale research project in Japan is awaited.

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Feature Article: Cryogenic Digital Devices
-Reversible Computing Using Adiabatic Superconductor Logic to Breakthrough the Minimum Energy Limitation Required for Logic Operations

Naoki Takeuchi, Senior Research Fellow
Nano ICT Laboratory, Advanced ICT Research Institute
National Institute of Information and Communications Technology

In order to realize the next generation high-end computers exceeding ExaFLOPS, an innovative logic circuit with much lower power dissipation than CMOS circuits is required. A common theme emerging in the pursuit of greater efficiencies in computation has long since involved the relationship between computer and energy. Amongst the arguments involved Landauer's principle [1] is well known. He predicted, "There is no minimum energy limitation for computing if there is no reduction in entropy". Some recent experimental demonstrations reported by Bérut and his research team has confirmed the validity [2]. Under these conditions, it is therefore anticipated to produce reversible logic operations [3], which can perform computations with unlimited minimum energy dissipation accompanied with no changes in entropy. However, research examples demonstrating reversible computing achieved at a device level have yet to be reported.

Here, the author and his research team have joined in their efforts to realize practical reversible computing by employing Adiabatic quantum-flux-parametron (AQFP) [4,5], a low-power superconducting logic gate. AQFP gates can ultimately limit switching energies by adiabatically changing the circuit potential energy. Up to now, experimental demonstrations of 10 zJ bit-energy operations [6] as well as demonstrations of sub-k_BT bit-energy operations using numerical analysis [7] have been successfully undertaken. Additionally, it has been proved that the energy-time product was engineered as having approximately the small dimensions of the quantum-mechanical limit ($\hbar/2$) [8]. The author considers these research findings to show that AQFP logic is a good candidate for use as a low-power building block composed of actual reversible computing.

A physically reversible device is desired in circuit design in order to perform reversible logic operations, [9]. Figure 1a shows a reversible quantum-flux-parametron (RQFP) gate [10], which the author's research team has proposed as reversible logic gate. The RQFP gate comprises of three Splitter (SPL) gates and three Majority (MAJ) gates. Since SPLs and MAJs have the same circuit topography as an AQFP logic circuit, an RQFP gate is symmetrical or proven to be physically reversible. Figure 1b shows simulation data of the energy dissipation for a logic operation using a RQFP gate. For all input data combinations the energy dissipation decreases almost linearly with an increase in the rise/fall time for AC bias currents, demonstrating that there is no minimum energy dissipation for reversible logic operations. The reason behind this is because the potential energy of all AQFPs comprising RQFP gates varies adiabatically as a result of the physical reversibility characteristics. The above-mentioned research findings successfully demonstrated the first practical reversible computing using RQFP gates with unlimited minimum energy dissipation. RQFP logic operations were also demonstrated successfully utilizing Nb integrated circuit fabrication process technology developed by the Advanced Industrial Science and Technology.

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In non-adiabatic circuits that include CMOS, large amounts of power exceeding k_BT for computation are required since the minimum energy dissipation is thermodynamically determined. Contrary to this, reversible computing utilizing RQFP gates proposed in this article can perform low-power logic operations with smaller amounts of energy than k_BT, which is anticipated to be greater than six-order superiority from a high-energy efficiency viewpoint. Future plans include further research studies towards the realization of practical ultra low-power reversible computation using RQFP gates.

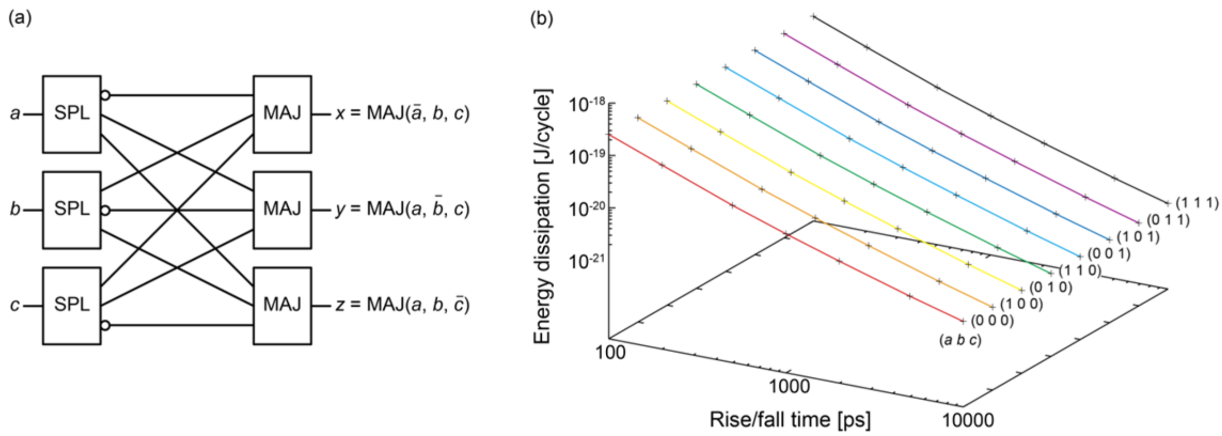

Fig. 1 RQFP gate (a) Block diagram – MAJ (*a*, *b*, *c*) = *ab*+*bc*+*ca*, (b) Simulated energy dissipation. Horizontal axis shows a rise/fall time of AC-bias currents. Simulated energy dissipation including input/output buffer energy consumption

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Feature Article: Cryogenic Digital Devices
-Superconducting Detector and Hybrid Device Using SFQ Circuits

Takekazu Ishida, Professor
Graduate School of Engineering, Osaka Prefecture University

Osaka Prefecture University (Ishida) and Nagoya University (Fujimaki) have proposed a basic principle to detect changes in kinetic inductance in the time domain triggered by different external sources along a current-biased superconducting nanowire, proving the transient voltage pulse. The detector is termed a current-biased kinetic inductance detector (CB-KID), and the diagram in Figure 1 shows its principle of operation. The detector can be applicable in a variety of external-signal detection applications. High-quality as-grown Nb thin films were patterned in a compact meander geometry producing a Nb nanowire. The central part of the meander-patterned Nb nanowire is enriched with a ^{10}B (200 nm) utilizing Molecular Beam Epitaxy (MBE). Here, the Nb nanowire remains superconductive when current flows. The research team based at Osaka Prefecture University have demonstrated that nuclear reactions between neutrons and the boron nuclei in the multilayer boron film breaks some Cooper pairs in the superconducting Nb nanowires since the nuclear reactions yields ^{4}He-^{7}Li nuclei releasing significant thermal energies of 2.3 MeV in the opposite direction. Thus, the demonstrations have verified that the breakage of some Cooper pairs caused a change in kinetic inductance, leading to the capability of neutron detection by measuring the transient voltage signals.

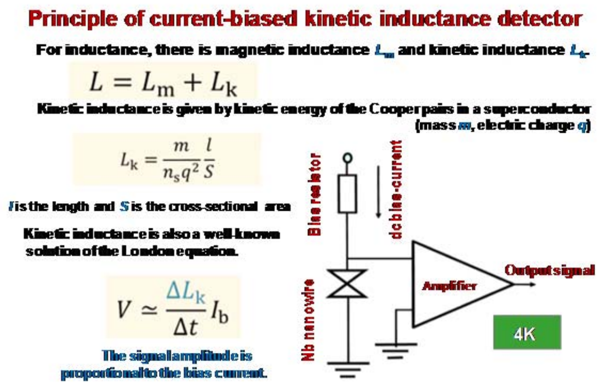

Fig. 1. Principle of current-biased kinetic inductance detector

Whilst conventional neutron detectors require large-scale high voltage power supplies, this new-type compact/lightweight neutron detector proposed by Osaka Prefecture University has been successful in detecting neutrons, offering advantageous operational characteristics at only several volts. The detector is not based on rare nuclear reactions of ^{3}He, and can be operated at 4K to detect changes in kinetic inductance. These advantages allow the assembly of single flux quantum (SFQ) circuits operating at 4K to be placed in series with multiplexing readout systems. As shown in Figure 2, the author's research team standardized an 80-pin package into 22 mm x

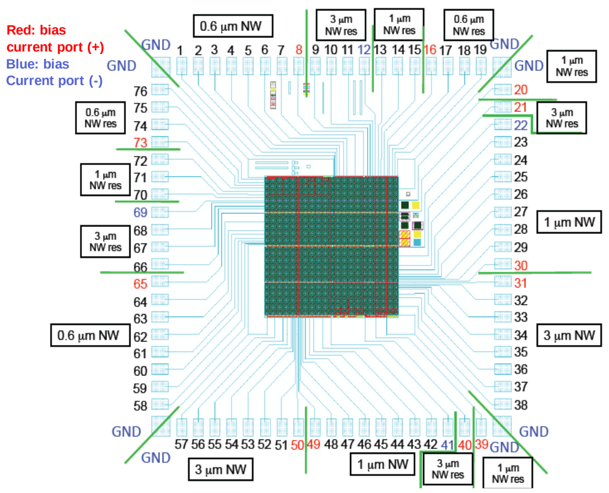

Fig. 2. The Nb nanowire detector mounted at the center of a 22mmx22mm Si-substrate, surrounded by 80-units of SFQ circuit electrode pads.

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22 mm size. By having X directional and Y directional sensor arrays, it is possible to assemble the superconducting detector (CB-KID), the neutron reactive layer (^{10}B) and single flux quantum (SFQ) read-out circuit all together onto a single chip. This could potentially lead to a superconducting chip similar to semiconductor-based CMOS. Scaled–down 0.6μm-wide Nb nanowaire with sub-micron spatial resolution could revolutionize technology able to realize one million pixels imaging in the near future. Specifically, the detector is of interest as a performance enhancement for SFQ read-out circuit.

At the Japan Proton Accelerator Research Complex (J-PARC), demonstrations of neutron detection using pulsed neutrons have concluded. Figure 3 shows a picture of the demonstration system with the element mount that was utilized. Practical realization of this new imaging system will pave the way for neutron detectors having ultra-high speeds, greater resolutions and ultra-high spatial resolution capabilities, as the potential tool applicable towards innovating existing technologies, neutron intensity measurements at nuclear reactor sites, non-destructive testing, new materials development and local-field distribution such as spintronics. Ultimately, further contribution towards progress in material science and magneto-science is anticipated.

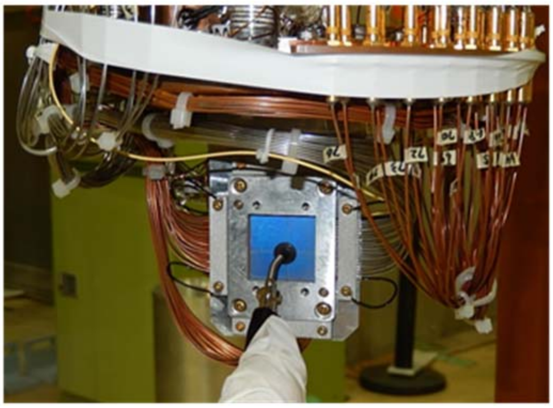

Fig.3. 4K refrigerator cryostat and 76-units of semi-rigid cables having the CB-KID installed in the middle

This research was undertaken in collaborations with Osaka Prefecture University (Takekazu Ishida, Shigeyuki Miyajima, Hiroaki Shishido, Yoshito Narukami, Naoto Yoshioka, Hirotaka Nakayama, and Hiroyuki Yamaguchi), Nagoya University (Akira Fujimaki), AIST (Mutsuo Hidaka), J-PARC (Kenichi Oikawa, Masahide Harada, Takayuki Oku, and Masatoshi Arai). The research is also supported by the fundamental research (S) entitled “All solid state superconducting system for neutron radiography with one million pixels and submicron resolution” (Takekazu Ishida et al) Grant Number:23226019, and Materials and Life Science Experimental Facility based at the J-PARC, 2013P0800 entitled “Development and the application of neutron optical devices and detector system” (Takayuki Oku *et al*).

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