Constructing a Vector Scanning SQUID System

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Abstract We succeeded in fabricating a vector scanning SQUID sensor, which was optimized to reduce the noise and to enhance the sensitivity by choosing the screening parameter as $\beta_s = 1$. The sensors were fabricated by a superconductive foundry CRAVITY of Advanced Industrial Science and Technology (AIST) using AIST-STP2 standard process with the critical current density $J_c$ of Josephson junctions (JJs) 320 A/cm². Under this condition, the critical current $I_c$ becomes 12.5 $\mu$A in the areas of 2.2 $\mu$m x 2.2 $\mu$m of our SQUID. The sensitivity and resolution of sensors were also improved by reducing inner diameter and increasing the number of the pick-up-coil windings with employing of multi-layer technique. We designed the structure of vector pickup coils, of which the same distance is kept between each coil and the sample surface. In addition, the distance between the coils were just set at an integer multiple of a scanning step so that it becomes convenient in reconstructing a magnetic-field vector at a certain position. The fabricated SQUID sensors were operated properly, and characteristics were in good agreement with our design parameters. In order to construct the vector scanning SQUID microscope, we succeeded in connecting our sensor with a commercial flux-locked loop (FLL) readout circuit (Magnicon Inc., Model XXF-1). The spatial resolution of vector SQUID microscopy can be improved by using an XYZ piezo-driven scanner for the precise control of the pick-up-coil positions over the three-dimensional range of 5 mm x 5 mm x 5 mm with a step size of 10 nm at 4K. A Gifford–McMahon cryocooler with an anti-vibration mechanism will be used to conduct long-time measurements.

1. Introduction
A scanning SQUID microscope is well known to have an ultra-high-sensitive and low-noise character for measuring fields as low as 5 aT (5x10−18 T) [1] under noise levels as low as 3 fT/Hz [2]. Therefore, it is always necessary for us to optimize the magnetic field measurements. Besides, SQUID devices are employed as a powerful tool in various different fields such as magnetics, electronics, biology, spintronics, security analysis, agriculture, information technology, communication, material science, and physics[3]–[8]. In the purpose of observing vortex distribution in a superconducting film, Morooka et al. constructed a scanning SQUID microscope with a micro DC-SQUID[9]. The cryostat consumes liquid helium to control a temperature between 3-100K and a precise scanning stage using a stepping
motor. However, the magnetic field sensitivity of the sensor was limited to 4 nT/√Hz owing to the sensing area of pickup coil is 2 x 2 μm² and a Nb line width of 2 μm. In preceding studies, we have studied vortex distribution in a restricted superconducting plate[4], [5], [10]–[12] by using a commercial scanning SQUID microscope (SQM2000, Seiko Instruments [9]), in which a dc SQUID sensor was equipped with a 10-μm outer diameter of the pickup coil and the line width of 2 μm. Vortex images were observed clearly, and we showed that vortex distribution primarily depended on the symmetry of the geometrical pattern. However, the sensitivity and the resolution of the sensor were still restricted by a diameter of the pickup coil. For nondestructive analysis using SQUID sensor, Knauss et al.[13] built the MAGMA-C10 system to observe the magnetic field images in conducting failure analysis with different levels of the flip-chip packaging technology, where a small SQUID about 30 μm wide was used with the sensitivity of 20 pT. However, a single-turn pickup coil of the SQUID sensor seems not to have high sensitivity and fine spatial resolution enough to provide highly accurate fault analysis for small areas of the stacking layers. On the other hand, a typical scanning SQUID microscope has a single scanning pick-up coil and its SQUID readout circuit to obtain the distribution of local magnetic field component only along the Z direction. Therefore, a vector SQUID microscope is expected to give us an alternative tool not only for scientific research but also for various useful applications. In this study, we plan to construct vector scanning SQUID microscopy with a vector SQUID sensor fabricated by us[14], of which the sensitivity and spatial resolution are improved by reducing an inner diameter and increasing the number of pick-up-coil windings with the aid of multi-layer Nb technique. An XYZ piezo-driven scanner for controlling the positions of the pick-up coils is employed to provide an improved spatial resolution of magnetic field image.

2. Vector SQUID sensor

Figure 1 (a) shows a vector scanning SQUID fabricated by us [14], which was integrated on a 3 mm x 3 mm Si chip with the aid of Nb-based multi-layer technology. The vector pickup system was located at a tip of Si chip. In order to reduce the distance between vector pickup coil and the sample surface, we used a fine emery paper of roughness 5 μm to polish the tip of Si chip containing the pickup coils (see Figure 1 (b)). We succeeded in polishing the tip by the abrasion length of 70 μm to ensure a close distance between the Z-coil center and the end edge of the tip down to 15 μm. Therefore, the height of pickup coil from sample surface can be intentionally controlled by the Z-stage until the coils edge are directly touched on the sample surface and the Z-coil plate with a declined angle of 7 degrees (Figure 1 (b)). The geometrical configuration of our vector pickup loops was revised in this work compared to our

![Figure 1](image-url)
preceding publications [14]–[16]. Figure 1 (c) is the latest version with the following features. (1) The geometry of the pickup coils was chosen to be a rectangular instead of a circle. We consider that this is preferable in achieving an enhanced spatial resolution at a much finer level than an actual coil diameter by utilizing the numerical data processing which is based on the inverse Biot-Savart law for recovering a true local magnetic field at the sample surface from observation data obtained at a finer step scan[14], [17]. Our scanning system is able to scan at a step of 10 nm at 4K by using the piezo-driven XYZ stages. (2) The positions of three pickup coils were optimized so as to be orthogonal with each other, and the centers of pick-up coils were carefully placed along the same single line. This design provides us a simple means how to extract the three components of a magnetic field vector at the same distance between three pick-up coils and the sample surface. The distances of the Z-coil center to the X-coil center or the Y-coil center were set at an integer multiple of the scanning step to calculate a magnetic field vector at the same point (x, y, z) from three channel data of the XYZ scanning of the SQUID microscope. (3) We built the double-winding pick-up coils in order to increase the sensitivity of SQUID sensor twice. The pickup coil system was connected directly to a SQUID circuit through a stripline with a covering superconducting Nb film. We used a gradiometer structure to couple with a SQUID washer magnetically between a feedback coil and the readout SQUID signal for canceling external electromagnetic noises.

The parameters were designed in order to optimize the sensitivity and noise[18] with the screening parameter \( \beta = 2 L I_c / \Phi_0 \approx 1 \), where \( I_c \) is the critical current of a Josephson junction and \( L \) is the loop inductance which consists of the inductance of pickup coil, the inductance of strip-line and the inductance of two washers. We chose the AIST-STP2 standard process to fabricate our sensor. Therefore, the critical current density \( J_c \) of Josephson junctions (JJs) is 320 A/cm\(^2\) and the critical current \( I_c \) becomes 12.5 μA in the junction area of 2.2 μm x 2.2 μm. We estimated the inductance of loop of 83 pH, the inductance of Z pickup coil of 20 pH for Z-coil with the inner size 4 μm x 4 μm and the line width of 3 μm, and the inductance of X or Y pickup coil of 10 pH of the height 2 μm. The height of X and Y coils were limited by the thickness of four-layered Nb thin films and the SiO\(_2\) layers. Therefore, the effective areas of the X, Y pickup coils are different from that of the Z pick coil. We need a calibration experiment of the coil sensitivity and the numerical processing program as discussed in the preceding study[17]. Each inductance of two washers was chosen as 30 pH[18]. In order to remove the hysteretic behavior in the current–voltage curve of the SQUID sensor, two shunt resistors were connected in parallel with JJs [19], [20]. Thus, the voltage output across the SQUID was a single-valued function of an applied flux since we chose the Stewart-McCumber parameter as \( \beta = 2 \pi I_c R_{sh} C \leq 0.7 \) [21], where \( R_{sh} \), \( C \) are a shunt resistor and a self-capacitance of JJ, respectively. We calculated the \( C \) based on equation \( 1/C = 0.20 - 0.043 \log_{10} I_c \), where \( C \) is the capacitance in an area (cm\(^2\)) [22]. Therefore, we reached the condition of \( R_{sh} \leq 8 \) Ω. We chose \( R_{sh} = 7.8 \) Ω by taking into consideration of the standard fabrication process. The damping resistors, in parallel with washers, are chosen as 1 Ω.

3. Vector scanning SQUID system

Figure 2 shows the latest version of our vector scanning SQUID microscope, which consists of an XYZ piezo-driven scanner, a Gifford–McMahon cryocooler, a temperature controller, a fabricated vector SQUID sensor, and a commercial 3-CH FLL readout circuit (XFF-1 Magnicon GmbH). A vector SQUID sensor was mounted on a sensor holder (Figure 2 (c)) which was composed of a 100-μm thick cantilever (phosphor bronze), a spring plate and a twelve-pins-male connector in order to provide a soft contact between a sample and a sensor, and to make the sensor connected to the electronics system. A sample was set in face-to-face with the SQUID sensor with a declined angle of 7 degrees. The sensor holder was installed from the top of scanning SQUID system (Figure 2 (b)) and is able to slide forward for making contact with a female connector, which was soldered with 3 channel x 5 Beryllium-Copper wiring loom by following a standard prescription of connection of SQUID application with the Magnicon FLL readout circuit [23]. The flange at the top of SQUID mount is to hold SQUID sensor and to ensure a good thermal contact with the 4-K stage. The temperature of the sample is controlled by a heater and a temperature sensor. They were installed on the top flange to control the temperature by a temperature controller (Cryocon, Model 32C). The sample is mounted on a sample holder, which was
machined by oxygen-free Cu block. The sample holder was cooled down through a poor thermal conduction route to 4K stage. It took a long time for a sample stage to reach 4K in high vacuum through poor thermal conduction route, but the heat flux from the sample stage to the 4K stage can be reduced to a level less than 0.1 W and it would be enough to keep the temperature of cryostat stage at 4K within the limited cooling power of 1 W. A high resistance manganin wire of 59 Ω/m was twisted each other to wind around a copper block to provide a heater function without generating an undesired magnetic field. In order to monitor the temperature of the sample, the second temperature sensor was also installed inside of sample holder, and connected to the other channel of the temperature controller. We use an XYZ piezo-driven scanner for controlling the position of the sample. The sample holder is thermally linked with the 4K stage via a SUS316 stage as a poor thermal link to reduce the heat load to the refrigerator. Besides, we consider that the temperature stability of the piezo-driven scanner is important to ensure the best precision of the XYZ stage. The range in the XY plane and Z direction are scanned over 5 mm x 5 mm x 5 mm with a step of 10 nm at 4K which are controlled by the piezo-driven controller ANC350 motion controller (attocube systems AG). The leads from the vector SQUID sensor are fed to a vacuum connector (Lemo, EGG.3B.324.CLL) at room temperature through 15 Beryllium-Copper wiring loom, and the standard connector can be firmly coupled with the commercial Magnicon FLL readout circuit at the top of cryostat in order to keep the bandwidth 6 MHz and to reduce a disturbance from environment noises. We used a Gifford–McMahon cryocooler to decrease the temperature of the vector scanning SQUID down to 4K, which is beneficial to conduct a long-time measurement without consuming liquid helium. The commercial SQUID microscope uses liquid helium, and the measurement time is typically limited less than 24 h even if we consume 100 L of liquid helium. This is not preferable in view of conducting systematic measurements required in vortex physics under the various different conditions. We canceled an AC noise from high power compressor by setting an insulating connector in high-pressure helium line from the compressor to the GM cryocooler. The cryocooler has anti-vibration mechanism, where the main cryostat has a bellows tube and screws isolated with silicone-washers between vibrating flange and the anti-vibrating flange. Inside of the cryostat, we separated the vibration and anti-vibration sections, of which the thermal links are connected by Ag-coated high-purity
soft Cu mesh wires. We coded a LabVIEW (National Instrum. Inc.) program to control all of the equipment via the USB interface or the GPIB interface.

4. Experimental results

First, we have to test the SQUID sensor designed for our vector scanning SQUID microscope. For this purpose, we set a thin-wire field coil with a diameter of 10 mm on a test package and attached in a sample holder [14]. We set the center of field coil at the tip of the vector SQUID sensor so that the field coil is able to apply the magnetic field to all the XYZ coils simultaneously in the cryostat for conducting measurements by the curve tracer [14]. We used a current source (Keithley Inc., Model 2400) to feed a dc current to the field coil for generating an external magnetic field to the vector SQUID sensor. The small field coil does generate inhomogeneous magnetic field, and is hence suitable for providing the three components simultaneously at the XYZ coils. We argue that the magnetic field from the tiny field coil has a main Z component and smaller X and Y components. We cooled the temperature of the vector SQUID sensor down 4 K. The sensor was connected alternatively with the characteristic measurement system [14], the FLL readout circuit is used to measure the V-Φ characteristics and the voltage readout of sensor under an external magnetic field.

![Graph](image-url)

**Figure 3.** The comparison of the V- Φ characteristics with the voltage of readout circuit from Magnicon FLL readout electronics circuit, which was tuned to give \( V_{rd}=1.3 \) V against each \( \Phi_0 \) external magnetic field. The horizontal scale is to refer an estimated magnetic field for the Z component.

Figure 3 shows a comparison of the V-Φ characteristics of a vector SQUID sensor which was obtained by the measurement system constructed by us, and the output voltage from the FLL readout circuit at the same external magnetic field under the bias current of 35 µA. The graph of the V-Φ characteristics shows that the magnetic field was measured not only by the Z pick-up coil but also by the X and Y coils. There, the periods of the V-Φ characteristics of X, Y, Z coils correspond to the magnetic field intensities which were estimated at the coil center of 34 A/m, 40 A/m and 16 A/m, respectively. We found that the field sensitivity against of the Z-magnetic field is the highest while it is lower in X and Y components of the magnetic field. While the thin-wire field coil generates an inhomogeneous magnetic field with the three components, the Z component is the main one in perpendicular to the Z pickup coil. On the other hand, the smaller areas of the X and Y pickup coil inducted a lower flux sensitivity compared to the Z
coil. We can reasonably understand the different field sensitivity against measured by the X, Y and Z coils. Therefore, we confirmed the proper operation of a vector SQUID sensor to measure a vector magnetic field in the present studies. We also demonstrated that the commercial Magnicon FLL readout electronics circuit worked well to measure the three channels from the X, Y, and Z SQUID outputs. The output voltage from the readout circuit was linearly proportional to the external magnetic field and was sensitive to the polarity in the X, Y, and Z channels. According to Fig. 3, we were successful in converting from the flux-sensitive oscillation of the vector SQUID sensor to a voltage output of the Magnicon FLL readout circuit. In the Magnicon FLL readout circuit [23], we used a SQUID Viewer software to tune the conversion ratio of the FLL-output voltage per one flux quantum so that the output voltage of the readout circuit increases by 1.3 V with a one-period increase in the SQUID-loop flux. Our method is surely useful to reconstruct a vector image mapping of any magnetic fields. We believe that our vector SQUID sensor is compatible with the commercial Magnicon FLL readout circuit in converting the $V$-$\Phi$ characteristic to the voltage of readout circuit.

5. Summary
We designed the vector SQUID sensors and fabricated them successfully. We confirmed that our sensor is suitable for constructing a vector SQUID microscopy system. We used the measurement system built by us to investigate the fundamental characteristics of 3D SQUID sensors, systematically. We confirmed that our sensors showed a good performance, which is suitable for our novel SQUID microscope. We revealed that the voltage outputs were adequate since a commercial SQUID readout circuit were operating properly. The results were in good agreement with the profiles of the $V$-$\Phi$ characteristics. We are almost at the final stage in constructing a novel SQUID microscope before completing the apparatus.

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