Vector sensor for scanning SQUID microscopy

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Abstract We plan to build a novel 3-dimensional (3D) scanning SQUID microscope with high sensitivity and high spatial resolution. In the system, a vector sensor consists of three SQUID sensors and three pick-up coils realized on a single chip. Three pick-up coils are configured in orthogonal with each other to measure the magnetic field vector of X, Y, Z components. We fabricated some SQUID chips with one uniaxial pick-up coil or three vector pick-up coils and carried out fundamental measurements to reveal the basic characteristics. Josephson junctions (JJs) of sensors are designed to have the critical current density $J_c$ of 320 A/cm², and the critical current $I_c$ becomes 12.5 µA for the 2.2µm x 2.2µm JJ. We carefully positioned the three pickup coils so as to keep them at the same height at the centers of all three X, Y, and Z coils. This can be done by arranging them along single line parallel to a sample surface. With the aid of multilayer technology of Nb-based fabrication, we attempted to reduce an inner diameter of the pick-up coils to enhance both sensitivity and spatial resolution. The method for improving a spatial resolution of a local magnetic field image is to employ an XYZ piezo-driven scanner for controlling the positions of the pick-up coils. The fundamental characteristics of our SQUID sensors confirmed the proper operation of our SQUID sensors and found a good agreement with our design parameters.

1. Introduction

A DC Superconducting quantum interference device (SQUID) consists of a superconductor ring and two Josephson junctions (JJs). It was invented by Jaklevic et al. of Ford Research Labs [1] after theoretical prediction of the effect in 1962 by Josephson [2]. The SQUID devices are useful in various fields such as magnetics, electronics, biology, spintronics, security analysis, agriculture, information technology, communication, material science, and physics [3-9]. In those applications, the DC SQUID is very sensitive to the magnetic field because it utilizes an interference effect of two JJs [10,11]. Therefore, it has been an essential component in constructing scanning SQUID microscopy for mapping a local magnetic field. A conventional 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.

In order to obtain a vector magnetic field, we proposed a vector scanning SQUID microscope with high sensitivity of magnetic field and high spatial resolution of local field mapping [12]. Ketchen et al. also studied a vector pick-up system using three SQUIDs with a vector pick-up coil [13]. We intend to realize a scanning SQUID microscope with high spatial resolution without losing the merit of high sensitivity in magnetic field. This possibly comes from reduced size in the pick-up coil. It has been known for a long time that a legacy SQUID sensor has a trade-off relationship between sensitivity and spatial resolution. Since an inductance of pick-up coil is a good measure of identifying the sensitivity of sensor, the increased diameter of the pick-up coil would enhance the sensitivity of the SQUID sensor. However, it also yields to lose a spatial resolution, directly. In addition, a SQUID microscope requires a lift-off distance between the sample surface and the SQUID pick-up coil. Therefore, the actual observation of the local magnetic field has a deteriorated spatial resolution than that of the original magnetic field distribution at the sample surface. If a lift-off distance is different among three pick-up coils, it gives a difference in the broadening effect on each coil. Regarding this annoying problem, we employ a multiple winding pick-up coil with the aid of the Nb multi-layer fabrication process of the CRAVITY facility of Advanced Industrial Science and Technology (AIST). Our system consists of three SQUID sensors with the three pick-up coils, which are located along the single line and are orthogonal with each other for sensing X, Y and Z components.

2. Design to fabricate SQUID Sensor.

Figure 1 shows the schematic equivalent circuit of the sensor of one-coil SQUID designed by us. A pick-up coil is connected directly to a SQUID washer, where two JJs of a DC SQUID were designed to have the critical currents $I_c$ of 12.5 μA. We employ a feedback coil in a gradiometer structure, which couples with SQUID magnetically in order to reduce the effect of external magnetic noise.

![Figure 1. Equivalent circuit of a SQUID sensor with one pick-up coil for sensing a magnetic field. $R_1$, $R_2$, and $R_3$ are damping resistors, and $R_{sh}$ is a shunt resistor for each JJ. The circuit parameters are designed as $R_1 = R_2 = R_3 = 1 \, \Omega$, $R_{sh} = 7.8 \, \Omega$, $I_c = 12.5 \, \mu A$, $L_{coil} = 10 \, \mu H$, $L_{wash} = 50 \, \mu H$, and $M_h \sim 50 \, \mu H$.](image)

The SQUID sensors were designed by using a CADENCE layout editor software in the standard AIST-STP2 for the multi-layer Nb thin film. We consider that the sensitivity and the resolution of a sensor are primarily dominated by the inductance of pick-up coil or equivalently by the size of coil. The geometry of the pick-up coil affects the procedure how to scan the coil during measurements and how to process observed data to recover the magnetic field at a certain point. Therefore, we designed to
fabricate three different type pick-up coils as shown in Figure 2. Figure 2 (a) shows a single-turn pick-up coil in a circular form with an inner diameter 8 µm. Figure 2 (b) shows a double-turn pick-up coil in a circular form with an inner diameter 6 µm. We intend that the effective area of the coil (a) is similar to that of coil (b). We expect that both sensors have a similar sensitivity and a similar inductance while the number of windings is different from each other. Due to the smaller diameter, the coil (b) is supposed to have a higher spatial resolution than the coil (a). Figure 2 (c) shows the pick-up coil in a square form with an outer size 10 µm. We consider that the square coil (c) is suitable for achieving an enhanced spatial resolution when the scanning is done in the 2D Cartesian coordinate in a step, which is appreciably smaller than the coil diameter. The coil (c) is also preferential in treating the data procession in our numerical method of the inverse Biot-Savart law for recovering a true local magnetic field at the sample surface [14]. We can easily define a pixel with the size smaller than the pick-up size by comparing a difference of magnetic flux between data at (i, j) position, the (i+1, j) position, and the (i, j+1) position, where indices i, j are row and column of scanning mesh, respectively. Our scanning system is able to scan at a step of 10 nm at 4K by using the piezo-driven XYZ stages.

The SQUID sensors were designed by us and were fabricated with the aid of the CRAVITY process, where the number of Nb layers is kept at four and the critical current density $J_c$ of a JJ is 320 kA/cm² [15-18]. Figure 3 shows a photograph of a typical vector SQUID sensor, and shows that the sensor was fabricated successfully. The design in the present work is an improved version of that employed in our preceding reports [12,19]. We revised the positions of three pick-up coils on the chip. They are not only orthogonal with each other, but the centers of pick-up coils are also located along the same line. This makes it possible to keep the same distance between three pick-up coils and the sample surface (see an enlarged photo of the three coils in Figure 3). This means that the vector pick-up coil catches the three components of a magnetic field vector at the same height from the sample surface. We suppose that the distance between the Z-coil center and the X-coil center can be chosen as an integer multiple of the scanning step. The distance between the Z-coil center and the Y-coil center is also chosen in a similar fashion. We plan to develop the measurement software so as to synthesize a magnetic field vector at the same point from the XYZ scanned data of the SQUID microscope to assist data acquisition. The sensitivity of the vector pick-up coil is designed to be improved by a factor of two by using a double-winding pick-up coils. Our vector SQUID sensor was fabricated on a chip size of 2.9 mm x 2.9 mm, and the vector pick-up coil is located at a corner of the chip. Our DC SQUID sensor consists of two JJs, which were designed to have a junction area of each JJ of 2.2 µm x 2.2 µm and the critical current $I_c$ of
12.5 µA. It was reported that the typical variation in JJ critical currents is better than 2% [20]. In each single sensor, the pick-up coil is connected to a SQUID washer directly, which was covered fully by superconducting Nb film. In order to reduce the external electric noise in the readout SQUID signal, we used a gradiometer structure with a feedback coil, which is fully coupled with a SQUID washer magnetically (Figure 2 (d)).

![Figure 3. Photograph of a typical vector SQUID sensor fabricated by us. Inset is an expanded photo of the vector three XYZ pick-up coils with two-turn windings. They are orthogonal to each other and their center positions are located along a single line at the same height from the sample surface.](image)

3. Measurement Results
In order to measure the characteristics of a vector SQUID sensor, we constructed a measurement system of the $I$-$V$ curve as described in Figure 4. We use a Gifford–McMahon cryocooler to reduce the temperature of a SQUID sensor down to 4 K. This refrigerator is able to measure the $I$-$V$ curve for long-time data acquisition in liquid helium at 4 K, and the temperature can be cooled down to 1.5 K for 60 minutes by pumping our liquefied helium in the sample space. The cryostat system was fully suitable for measurements at high frequencies because we use the semi-rigid coaxial cables and SMA connectors for leads from room temperature down to cryogenic temperatures. A digital-analog converter DAC (National Instrument Inc., NI9263 module) has a resolution 16 bit to feed a voltage in the range of ±10V with a 0.3-mV resolution. The operation speed reaches 100 k/s/ch, the output impedance is lower than 0.1 Ω and a current driver of 1 mA which are fine enough to cover a necessary current to apply a SQUID sensor. An analog-digital converter ADC (National Instrum. Inc., NI9239 module) has a resolution 24 bit, an input noise lower 70 µVrms, and an input impedance as large as 1 MΩ. This means our system has a resolution of 2 µV and the full-scale ranges ±10V in a single range. In order to improve the performance of the ADC module and to reduce the noise of signal, we used a low noise preamplifier (Ithaco Inc., Model 1201) with a high input impedance (100 MΩ) and a variable gain from 10 to 1000. A current source (Keithley Inc., Model 2400) can feed the desired current with a computer via the GPIB interface. A temperature controller (Lakeshore Inc., Model 340) was used to monitor and control the temperature of a SQUID sensor. We also installed the several low pass filters (LPF) consisting of R, C components to reduce the noise in the signal produced by the DAC module, the current source, and the commercial power line. All of the equipment were connected to the computer by the USB interface or the GPIB interface, and were controlled by a LabVIEW (National Instrum. Inc.) program coded by ourselves. The SQUID sensor is shielded both by the double-wall permalloy cylinders at room temperature and the single-wall cryogenic permalloy cylinder at 4K.
Figure 4. The $I$-$V$ curve measurement system for testing the SQUID characteristics. The system is controlled by a LabVIEW program. The cryogenic temperature is achieved by a Gifford-McMahon cryocooler. We inserted several passive filters to reduce the noise in measurement signals.

Figure 5 shows the typical $I$-$V$ curves of three XYZ channels of the SQUID sensor on the same chip (a vector SQUID sensor as in Figure 3). The measurement results were obtained as the three-different $I$-$V$ curves, of which the characteristics are almost the same with each other (see Figure 5). This confirms that our design to fabricate the three XYZ sensors is precise enough to work properly under the same condition. The critical current $I_c$ of each sensor is 27 $\mu$A, which is in good agreement with our design value of 25 $\mu$A ($= 2 \times 12.5$ $\mu$A). We installed an additional coil of 20 turns in our system to produce an external magnetic field at the position of the sensor, where the pick-up coils were placed at the center of the 20-turn coil. We applied an external magnetic field so as to adjust a current fed into the 20-turn coil. The inset of Figure 5 shows that there is an oscillation in the $I$-$V$ curves when the external magnetic field is changed systematically. All of the measurement results confirm that we fabricated the vector SQUID sensors successfully as designed by us.

We also measured an inductance of pick-up coil by using a test chip, which was fabricated simultaneously on the same wafer with the vector SQUID sensors with an additional lead to feed an additional current to the coil to know an inductance. By applying a controlled current directly through two terminals of pick-up coil, we found the periodic oscillation of the $I$-$V$ curve. From the period of the oscillation, we identified the inductance of Z pick-up coil as 10.35 pH and the inductance of XY pick-up coils as 9.86 pH. Those results give us sound evidence that our fabrication is good enough to make sure a proper operation as intended in our design. We note that the inductance of the X pick-up coil is almost the same with those of the Y and Z coils. This again indicates that the sensitivity of three XYZ sensors is supposed to be approximately the same with each other.
The voltage of sensor (V) of 27 µA (typical). The SQUID sensor is cooled down to 4.2 K using a Gifford–McMahon cryocooler.

We confirmed that this shift in the voltage of sensor (V) shows the three period characteristics of the external applied magnetic field when the bias current to the feedback coil.

In Fig 5, we show the I-V curve under the various different magnetic field used for the SQUID modulation.

Figure 6 shows the V-Φ characteristics of the sensor S1 (see Figure. 2(a)) and the sensor S2 (see Figure. 2(b)) when an external magnetic field is changed systematically under the SQUID bias current I_b of 30 µA. We find that the sensor S2 shows the four periods of the Φ_0 oscillation while the sensor S1 shows the three periods of the Φ_0 oscillation in 60 µT. They can be interpreted that the areas of sensor 2-turn pick-up coil (226µm²) is slightly larger than that of the single-turn pick-up coil (201 µm²). Therefore, the inductance of the 2-turn coil is higher than that of the single-turn coil, and it is responsible for the higher sensitivity of the sensor S2 than the sensor S1. This confirms that our idea to improve the inductance of pick-up coil works well. In addition, the magnetic field penetration into the coil wire should be taken into account in estimating the effective areas of the pick-up coils. We are going to investigate further in this respect in our future work.

Figure 6. The V-Φ characteristics of the dc SQUID sensors. The sensor S1 has a single-turn pick-up coil while the sensor S2 has a two-turn pick-up coil. The sensor voltage was measured as a function of the external applied magnetic field.

To understand the proper operation of our SQUID sensor or to simulate the operation of flux locked loop (FLL), we feed a current into the feedback coil when the SQUID sensor is biased under a certain current. When an external magnetic field is applied to the coil, the voltage of the sensor changes systematically. We confirmed that this shift in the voltage could be compensated by feeding a proper current to the feedback coil. In Figure 7, we show the current applied to feedback coil of the SQUID sensor as a function of the external magnetic field when the bias voltage of the SQUID sensor is kept at 190 µV. The first operation point, the second operation point, etc. respectively show the working points.
in the different periodic branches of the $V\cdot\Phi$ characteristics with the step $\Phi_0$ of each branch. We consider that this is sound evidence to convince that our SQUID sensor works properly even if it is used in an FLL mode as designed by us.

![Figure 7](image.png)

**Figure 7.** The external magnetic field as a function of current fed into the feedback coil. We find a good linearity of the external magnetic field as a function of feeding current in the periodic $V\cdot\Phi$ characteristics.

In the next step of our research, we are going to install our sensor with a commercial SQUID readout circuit (Magnicon Inc., Model XXF-1) to achieve an automatic measurement system for the XYZ three channels.

4. **Summary**

We successfully fabricated the SQUID sensors to construct a scanning XYZ vector SQUID microscope. A vector scanning SQUID sensor was fabricated on the single chip by using the Nb multi-layer process. The characteristics of the different SQUID sensors have been investigated systematically by using a laboratory-made measurement system. Our measurements such as the $I-V$ curves and the $V\cdot\Phi$ curves were used to obtain the critical current of the SQUID sensors and the inductance of the pick-up coils. We confirmed that our sensor worked properly as we designed by using the CAD system. We are under construction of the cryogenic system with an XYZ piezo-driven scanner to realize a vector SQUID microscope.

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